Vol. 25, No. 4 PSYCHOLOGICAL REVIEW PUBLICATIONS July, 1918

Psychological Review

EDITED BY

HOWARD C. WARREN, PRINCETON UNIVERSITY
JOHN B. WATSON, JOHNS HOPKINS UNIVERSITY (*J. of Exp. Psychol.*)
JAMES R. ANGELL, UNIVERSITY OF CHICAGO (*Monographs*)
SHEPHERD I. FRANZ, GOVT. HOSP. FOR INSANE (*Bulletin*) AND
MADISON BENTLEY, UNIVERSITY OF ILLINOIS (*Index*)

ADVISORY EDITORS

R. P. ANGIER, YALE UNIVERSITY; MARY W. CALKINS, WELLESLEY COLLEGE; H. N. GARDINER, SMITH COLLEGE; JOSEPH JASTROW, UNIVERSITY OF WISCONSIN; C. H. JUDD, UNIVERSITY OF CHICAGO; ADOLF MEYER, JOHNS HOPKINS UNIVERSITY; W. B. PILLSBURY, UNIVERSITY OF MICHIGAN; C. E. SEASHORE, UNIVERSITY OF IOWA; G. M. STRATTON, UNIVERSITY OF CALIFORNIA; MARGARET F. WASHBURN, VASSAR COLLEGE.

CONTENTS

Associative Aids: II. Their Relation to Practice and the Transfer of Training: H. B. REED, 257.

Intelligence as Estimated from Photographs: RUDOLF PINTNER, 286.

The Genesis of the Image: CURT ROSENOW, 297.

The Heterochromatic Differential Threshold for Brightness: I. Experimental: LEONARD T. TROLAND, 305.

The Rate of Pupillary Dilation and Contraction: PRENTICE REEVES, 330.

PUBLISHED BI-MONTHLY BY
PSYCHOLOGICAL REVIEW COMPANY
41 NORTH QUEEN ST., LANCASTER, PA.
AND PRINCETON, N. J.

Entered as second-class matter July 13, 1897, at the post-office at Lancaster, Pa., under Act of Congress of March 3, 187

Psychological Review Publications

EDITED BY

HOWARD C. WARREN, PRINCETON UNIVERSITY (*Review*)
JOHN B. WATSON, JOHNS HOPKINS UNIVERSITY (*J. of Exp. Psych.*)
JAMES R. ANGELL, UNIVERSITY OF CHICAGO (*Monographs*)
SHEPHERD I. FRANZ, GOVT. HOSP. FOR INSANE (*Bulletin*)
MADISON BENTLEY, UNIVERSITY OF ILLINOIS (*Index*)

WITH THE CO-OPERATION OF
MANY DISTINGUISHED PSYCHOLOGISTS

PSYCHOLOGICAL REVIEW

containing original contributions only, appears bimonthly, January, March, May, July, September, and November, the six numbers comprising a volume of about 480 pages.

PSYCHOLOGICAL BULLETIN

containing critical reviews, notices of books and articles, psychological news and notes, university notices, and announcements, appears monthly, the annual volume comprising about 480 pages. Special issues of the BULLETIN consist of general reviews of recent work in some department of psychology.

JOURNAL OF EXPERIMENTAL PSYCHOLOGY

containing original contributions of an experimental character, appears bimonthly, February, April, June, August, October, and December, the six numbers comprising a volume of about 480 pages. [Temporarily suspended.]

PSYCHOLOGICAL INDEX

is a compendious bibliography of books, monographs, and articles upon psychological and cognate topics that have appeared during the year. The INDEX is issued annually in May, and may be subscribed for in connection with the periodicals above, or purchased separately.

ANNUAL SUBSCRIPTION RATES

Review and Bulletin: $6 (Foreign, $6.50). Journal: $3.25 (Foreign, $3.50).
Review and Journal: $6 (Foreign, $6.50). Bulletin: $3.25 (Foreign, $3.50).
Journal and Bulletin: $6 (Foreign, $6.50).
Review, Bulletin and Journal: $9 (Foreign, $9.75).
Index with any other two: $7 (Foreign, $7.50).
Review, Bulletin, Journal and Index: $10 (Foreign, $10.75).
Current Numbers: Review, 65c; Bulletin, 35c; Journal, 65c; Index, $1.25.

PSYCHOLOGICAL MONOGRAPHS

consist of longer researches or treatises or collections of laboratory studies which it is important to publish promptly and as units. The price of single numbers varies according to their size. The MONOGRAPHS appear at irregular intervals and are gathered into volumes of about 500 pages with a uniform subscription price of $4.. (Postal Union $4.30.)

Philosophical Monographs: a series of treatises more philosophical in character.

Library of Genetic Science and Philosophy: a series of bound volumes.

Subscriptions, orders, and business communications may be sent direct to the

PSYCHOLOGICAL REVIEW COMPANY
Princeton, New Jersey

FOREIGN AGENTS: G. E. STECHERT & CO., London (2 Star Yard, Cary St., W. C.); Paris (16, rue de Condé)

VOL. 25. NO. 4 July, 1918

THE PSYCHOLOGICAL REVIEW

ASSOCIATIVE AIDS: II. THEIR RELATION TO PRACTICE AND THE TRANSFER OF TRAINING

BY H. B. REED

University of Idaho

III

The methods and materials for this experiment were the same as those described in my paper on 'The Relation of Associative Aids to Learning, Retention, and other Associations.' As stated there, the tests were repeated every day for six days, and on the sixth day, the *B*, *D*, and *U* tests were given in addition. The former enable us to detect the effect of repeated learning or practice upon associative aids, and the latter enable us to detect their influence upon the transfer of training in so far as this means the effect of learning things in one connection upon learning them in a different connection. The solution of these two problems will form the burden of this paper.

The nature of our experiment enables us to measure practice effect in various ways and also to isolate several factors influencing the cause of practice. The former may be measured (1) by the average number of repetitions, *R*, per pair for each day; (2) by the average reaction time, *T*, per pair for each day, and (3) by the number of pairs correctly remembered each day, *NC*. Since the time was taken for every reaction, wrong or right, we were able to tell to what extent practice effect is due to the elimination of errors and to what extent it is due to the improvement in the times of the correct reactions, *CR*. All of these measures were cal-

culated for each individual for each day and test, and their averages for all of the subjects of the experiment. The reliability of these averages was measured by a calculation of the A.D.'S for the group averages. In addition, the A.D. of the Ave. L.T. or T. of each individual for each day was calculated and this measure is called *TAD*. The group average of *TAD* and its A.D. were also calculated. The *TAD* therefore measures the variation of the individual in his own L.T.'s, and the A.D. of the group average of the *TAD* measures the variation of the individual *TAD*'s among each other. The group averages for each day and test of all these measures together with their A.D.'s appear in Table VIII. Following our custom, we have kept the measures of each series separate and in the last section of the table we have given the general averages for all the series.

If we imagine curves for the respective averages in Table VIII, it will be seen that the *R*, *T*, *TAD*, and *CR* curves all

TABLE VIII

SB

	1	2	3	4	5	6	*B*	*D*	*U*
R.....	1.89	.51	.16	.08	.03	.05	.14	.98	1.26
AD....	.58	.21	.12	.10	.04	.08	.09	.62	.66
T.....	7.25	4.25	2.55	1.99	1.65	1.65	2.47	7.85	8.43
AD....	3.08	1.26	.54	.64	.69	.49	.62	4.61	2.30
TAD...	4.30	2.02	1.10	.92	.86	.80	1.68	4.55	5.69
AD....	2.04	.95	.70	.60	.68	.67	1.07	2.05	1.16
CR.....	2.35	2.13	1.73	1.59	1.53	1.46	1.89	3.75	3.38
AD....	.62	.92	.46	.34	.42	.38	.39	1.05	.44
NC.....	4.56	5.92	8.44	9.16	9.65	9.55	8.33	3.55	2.70
AD....	1.44	1.08	1.44	.80	.56	.76	.55	1.70	.62
N.....	250	250	250	250	200	210	130	130	70

RC

R.....	1.67	.50	.15	.06	.04	0	.26	1.08	1.00
AD....	.29	.35	.19	.09	.05	0	.12	.84	.24
T.....	5.34	3.87	2.74	2.21	1.91	1.54	3.90	7.38	10.60
AD....	2.90	.76	1.46	.85	.39	.28	1.59	2.77	3.14
TAD...	3.19	2.15	1.45	1.37	.79	.50	2.42	5.08	5.64
AD....	1.85	1.29	1.15	.90	.47	.30	1.97	1.87	3.31
CR.....	2.05	2.22	2.01	1.85	1.75	1.51	2.36	2.55	2.64
AD....	.51	.46	.44	.65	.29	.24	.75	.81	.89
NC.....	5.09	6.59	8.77	9.36	9.47	9.84	7.77	4.16	2.78
AD....	.62	.65	1.44	1.07	.65	.28	.75	2.66	1.18
N.....	220	220	220	220	180	180	90	70	70

WS

R.....	2.55	.76	.37	.23	.18	.13	.51		.77
AD....	.59	1.02	.25	.15	.15	.13	.52		.55
T.....	11.89	6.25	3.90	3.10	2.49	2.31	3.52		8.32
AD....	3.85	3.76	2.44	1.52	1.20	1.03	4.46		4.11
TAD...	6.98	3.94	2.77	2.16	1.54	1.33	3.24		4.81
AD....	2.62	2.57	1.93	1.72	1.15	.97	2.04		2.87
CR.....	2.82	2.01	1.96	1.77	1.66	1.60	1.96		3.65
AD.....	.73	.40	.53	.77	.42	.21	.51		1.27
NC.....	2.52	6.63	7.11	8.15	8.76	8.63	7.00		4.86
AD....	1.65	1.86	1.57	1.48	1.01	.73	1.76		2.52
N.....	270	270	270	270	240	230	240		220

WP

R.....	4.30	1.40	.43	.23	.20	.13		1.16	
AD....	1.08	.75	.29	.24	.20	.15		.88	
T.....	17.50	8.29	4.20	3.15	2.66	2.09		13.36	
AD....	7.25	4.80	1.99	1.41	.94	.71		5.96	
TAD...	7.78	4.45	2.41	1.83	1.36	1.07		7.05	
AD....	3.81	2.32	1.42	1.08	.76	.42		3.80	
CR....	3.24	2.53	2.41	2.11	1.94	1.75		3.68	
AD.....	1.13	.75	.82	.63	.45	.57		1.38	
NC.....	1.07	3.30	7.00	8.11	8.61	9.00		2.50	
AD....	.76	1.90	2.07	1.51	.92	1.04		.93	
N.....	270	270	270	270	250	220		240	

General Averages

	1	2	3	4	5	6	*B*	*D*	*U*
R.....	2.60	.79	.28	.15	.11	.08	.23	1.41	1.01
AD....	.58	.58	.21	.15	.11	.09	.24	.78	.48
T.....	10.49	5.67	3.35	2.64	2.18	1.90	3.29	9.53	9.12
AD....	4.29	2.52	1.61	1.11	.86	.63	2.22	4.45	3.08
TAD...	5.56	3.14	1.93	1.57	1.14	.92	2.45	5.56	5.38
AD....	2.58	1.78	1.30	1.07	.77	.59	1.69	2.57	2.45
CR.....	2.62	2.22	2.03	1.79	1.72	1.58	2.06	3.33	3.22
AD.....	.75	.63	.56	.49	.39	.35	.55	1.08	.87
NC.....	3.31	5.61	7.83	8.69	9.12	9.26	7.70	3.40	3.45
AD....	1.13	1.37	1.64	.97	.78	.70	1.02	1.76	1.44
N.....	252	252	252	252	217	211	153	146	120

R = No. of repetitions per pair
T = Learning time in seconds
TAD = Ave. of *AD*'s of individuals in their *T*'s per pair
CR = Reaction time for correct responses
NC = No. of pairs correctly remembered
N = No. of pairs upon which averages are based.

have the same general shape. They fall rapidly for the first three days and very slowly for the other days. In the sixth day, they turn their direction, rising gradually for the *B*, *D*, and *U* tests respectively. The *NC* curve has just the reverse shape. These characteristics are shown clearly in Chart I,

which is based on the general averages at the bottom of table VIII. If we measure the difficulty of the different series by their height from the zero abscissa line, the order of difficulty beginning with the easiest is *SB*, *RC*, *WS*, and *WP*. It is noteworthy that the *CR* curve is the lowest one and has the flattest shape. But there is a very gradual fall from day

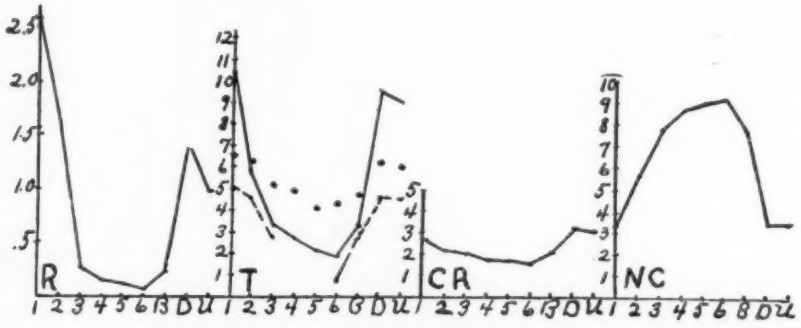


CHART I. Based on general averages in Table VIII. *R* = No. of repetitions per pair. *T* = Learning time in seconds. *CR* = Reaction time for correct responses in seconds. *NC* = No. of pairs correctly remembered. - - - - Dashes = No. of associative aids, general averages, Table IX. . . . . Dots = No. of associative aids, general averages, Table X. Abscissas = Days of practice and *B*, *D* and *U* tests.

to day. This shows that improvement is due principally to the diminution of error but it is also due in part to a shortening of the correct reaction from day to day, *i. e.*, a mechanizing of the correct responses.

If we wish to discover the relation of associative aids to the practice effect just described, we can do so by calculating the average frequency of the pairs that were associatively learned from day to day. As stated above, we recorded, after the learning of each series, the associative aids on the first, second, third, and sixth days for eighteen subjects, and after each response on each day for 9 subjects. The first procedure prevented the creation of artificial reports and interference with the natural course of associative aids by a continual stimulation of them. On the other hand, the second procedure enables us to picture the details of the course of associative aids that would be forgotten and omitted in the

former procedure. The results of the first procedure are given in Table IX and those of the second in Table X.

TABLE IX

TABLE SHOWING AVE. NO. OF ASSOCIATIVE AIDS IN THE 1ST, 2D, 3D, AND 6TH DAYS, AND IN THE *B*, *D*, AND *U* TESTS. FIRST PROCEDURE

SB							*RC*						
1	2	3	6	*B*	*D*	*U*	1	2	3	6	*B*	*D*	*U*
5.68	4.88	4.00	0.84	1.93	4.30	4.25	6.92	6.08	3.52	0.70	4.40	5.71	4.55
N =	250			140	63	108	*N* =	250			50	140	63
WS							*WP*						
4.60	4.32	1.66	0.72	2.40		5.00	3.68	3.33	2.44	0.56		4.10	
N =	250			150		171	*N* =	250				171	

From Table IX it will be seen that the frequency of associative aids decrease very little on the first two days, but on the third day they take a sharp drop, and by the sixth day have almost completely slumbered away. However, they are again slightly awakened by the *B* test and have become fully active in the *D* and *U* tests. There is thus a very close parallelism between the *R* and *T* curves, on the one hand, and the curves for the frequencies of associative aids on the other. This is shown in the dots and dashes with the *T* curve in Chart I. They are based on general averages calculated from Tables IX and X. This relationship means that associative aids disappear with practice and that their disappearance shortens the reaction time. My records

TABLE X

TABLE SHOWING AVE. NO. OF ASSOCIATIVE AIDS EACH DAY FOR INDIVIDUALS FROM WHOM VERBAL REPORTS WERE TAKEN AFTER EACH RESPONSE. SECOND PROCEDURE

SB									*RC*								
1	2	3	4	5	6	*B*	*D*	*U*	1	2	3	4	5	6	*B*	*D*	*U*
8.00	7.20	5.83	5.20	6.00	6.30	6.30			9.00	7.50	5.50	5.50	2.50	2.00		6.50	
N =	60			40		40			*N* =	20						18	
WS									*WP*								
5.00	4.40	4.25	3.75	2.71	3.66	3.20		6.33	4.86	6.37	5.75	5.50	5.50	5.66		6.33	
N =	80			60	60	54			*N* =	80			60	60		54	

show that a pair that was accompanied by an associative aid on the sixth day always had a longer reaction time than one that was not so accompanied. This is what we should expect, for, other things being equal, the more middle terms between a stimulus and a response, the longer the reaction time would reasonably be. From this principle as well as from the facts of Table IX., it is safe to assume that the disappearance of these middle terms is another factor conditioning the rate of improvement from day to day.

That the presence of associative aids should shorten the L.T. on the first and second days and lengthen it on the sixth day is not at all a contradiction in terms if we remember their natural course and the nature of the learning process. But in any case, however contradicting this may appear from the standpoint of logic, the facts of the matter force us to accept its rationality. During the early stages of learning, associative aids supply a connecting link between two unrelated terms and thus make an easy transition from one term to the next. If there is no such connecting link, the learner usually has to wait a little while until the response comes, and besides, has to make an effort to recall a fact, which always consumes a long time in comparison to a case where the connections are ready at hand. In neurological terms, we may think of an associative aid as supplying a roundabout conduction unit of low resistance between two newly stimulated cells. When one of these is stimulated the excitation travels readily to the other. When there is no associative aid, the excitation of the neurone for the one term is blocked and must travel slowly to the neurone for the next term because of the high resistance, and therefore results in a long reaction time. After a period of exercise, however, the synapses of the neurones for the new terms become open and the excitation travels rapidly and directly from the one to the other, producing the shortest possible reaction. A roundabout path is no longer necessary, and if the excitation travels through it, it requires that much more time. The associative aid is thus a means of opening the synapses or for reducing the resistance of the newly stimulated neurones, and when it has

once performed that function, the connection becomes direct. Or on the psychological side, the function of associative aids is to connect new terms, and when they have made that connection, they disappear.

From Table X the decrease in frequency of the associative aids is much slower than in Table IX. There is, however, a decrease, and it is the most marked in the *RC* or easiest series. This indicates that with this procedure it would simply take a longer time for the associative aids to disappear. The slow decrease shown in this table in comparison with Table IX makes it evident that the ever-recurring demand after each response to report what was thought of between the stimulus and the response not only kept the associative aids in a high degree of excitation but also engendered an attitude or set that favored such an excitation.

Having sketched the general course of associative aids as it is influenced by repeated learning, we may now illustrate it by examples from our records.[1]

First Procedure

	March 10	March 11	March 12	March 16
	5. Clean 1″			
	4. No 2″	4. Clean 1″		
	3. No 8″	3. No 3″		
	2. No 2″	2. No 4″		
Mistake clean	1. 0″	1. No 4″	1. Clean 1″	1. Clean 2.5″
First day	Nothing			
Second day	"			
Third day	"			
Sixth day	"			
	2. Tarry 2.5″			
Simmer tarry	1.	1. Tarry 2″	1. Tarry 1″	1. Tarry 1.5″

First day: Thought of something on the stove and tarrying a long time.
Second day: Same.
Third day: Same.
Sixth day: Nothing.

		March 10	March 11	March 12	March 16
Miss Jen.	5 P.M.	3. Time 4.5″			
		2. No 4.5″			
Galley time		1.	1. Time 3″	1. Time 2″	1. Time 1″

First day: Thought of boat with galley slaves, and it took a long time to get in the boat.

[1] For an explanation of the arrangement, see this volume, p. 139.

Second day: Same.
Third day: Same.
Sixth day: Nothing.

	3. Betide 1″			
	2. No 5″	2. Betide 1″	2. Betide 1″	
Space betide	1. 0″	1. No 8″	1. No 8″	1. Betide 1″

First day: Space between the tides.
Second day: Same after prompting.
Third day: Nothing.
Sixth day: Nothing.

SECOND PROCEDURE

Mr. Teh.

	May 18	May 19	May 20
8–9 A.M.	2. Coffee .8″		
Radish coffee	1. 0″	1. Coffee 2.6″	1. Coffee 1.6″

	May 21	May 22	May 24
	1. Coffee 1.7″	1. Coffee 1″	1. Coffee .5″

First day: Saw a radish and a cup and a saucer on the table.
Second day: Just the word coffee came into my mind.
Third day: Saw a radish, coffee came immediately.
Fourth day: Saw a red radish and a table, then the word coffee came.
Fifth day: Nothing.
Sixth day: Nothing; expected it.

	May 18	May 19	May 20	May 21
	2. Wall 2.3″			
Soup wall	1. 0.0″	1. Wall .6″	1. Wall 1″	1. Wall 1.2″

	May 22	May 24
	1. Wall 1.6″	1. Wall 1.8″

First day: I immediately connected these with serve-hold, waiter holding soup and spilling it on wall.
Second day: Just tray and then wall came.
Third day: Same.
Fourth day: Vague image of tray, then wall came.
Fifth day: Nothing.
Sixth day: Thought of Zool. Lab., then Miss Wall. She makes so much noise over there.

	May 18	May 19	May 20	May 21
	5. Lek 3.4″			
	4. Rem 13.6″			
	3. Rem 2.4″	3. Lek 2.3″		
	2. Zum 3″	2. No 10.6″		2. Lek .8″
Yab lek	1. 0.0″	1. No 4.6″	1. Lek 3.4″	1. No 8.″

	May 22	May 24
	1. Lek 1.4″	1. Lek 2.3″

First day: 2. Zum seemed right.
3. Rem seemed right.
4. Response has an *e*, had said rem but it was wrong, but I could think of nothing else.
5. Thought of rem, right response begins with letter before *m*, so I got it. Thought of this after last prompting.

Second day: 1. Only yab.
2. Thought of rem, not right because I tried it twice before; don't know.
3. Thought of rem, not right, response has an *e* in it and begins with first consonant before *m*.

Third day: Same.
Fourth day: Same, but could not think of lek.
Fifth day: First rem, then lek immediately.
Sixth day: Rem, then *lek*.

Miss Bro.

3–4 P.M.	May 24	May 25	May 26	May 27
Kimono-stencil	2. Stencil 2.4″ 1. 0.0″	Design 1. Stencil 2.6″	1. Stencil 1.6″	1. Stencil 1.4″

May 29	June 1
1. Stencil 1.8″	1. Stencil 1.0″

First day: Had picture of a design stenciled on kimono.
Second day: Same.
Third day: Thought of design, then stencil.
Fourth day: Only stencil.
Fifth day: " "
Sixth day: " "

The above examples enable us to picture the course of associative aids as they are influenced by repeated learning. The first procedure shows us that in some cases they come up almost in the same way for three experiment days, but have wholly disappeared by the sixth experiment day. In some cases they occur only on the first and second days; and in others only on the first day. This is in agreement with the frequency curves for the four series of pairs learned by 18 subjects. There is a gradual fall in the curves for the first three days, but by the sixth it touches the zero line. The second procedure has the advantage in enabling us to tell not only what happens to the course of associative aids on the fourth and fifth experiment days but also how they are influenced by repeated promptings on the same day. Mr. Teh.'s reports are enlightening in this connection. This

student had the benefit of two semester's work in both theoretical and laboratory psychology and had learned to become a skillful observer. For example, the pair 'troll-blast,' learned by him required four promptings, *R*'s, on the first day and an L.T. of 26.7″. Before the second *R*, he could think only of the stimulus, 'troll.' Before the third *R*, he could remember only that he was prompted. Before the fourth *R*, he again could think only of the stimulus. But he now succeeds in devising an association. He thinks of trolls as mountain spirits in one of Ibsen's dramas. The idea of mountain calls up mining, and mining calls up the idea of blast. He now has a connection between troll and blast, and the next time he responds correctly. On the second day, he recalls this association at once and has an L.T. of 2″. By the third day it has almost slipped away, but it comes back slowly and he has an L.T. of 5″. On the third day, he thinks of placing 'trolls' in a book, which immediately calls up blast. The intermediate links of 'trolls' in the mountains and mining, and of mining and of blast, have disappeared. On the fifth day, he thinks only of 'trolls' in a book. The idea of placing them definitely has disappeared. On the sixth day the response is immediate without any association, the L.T. being only 1″. The learning of 'yab lek' is another example showing in detail a similar psychological process. A third example may be taken from the learning of 'soup wall.' On the first day, Mr. Teh. thinks immediately of a previous pair, 'serve-hold,' then of a waiter holding soup and spilling it on the wall. By the second day, most of this has disappeared, and he thinks only of a tray and a wall. The same occurs on the third day. On the fourth day, the image of a tray becomes very vague, and on the fifth day, the response is immediate without any association or imagery. The example from Miss Bro. is a type of great frequency. In learning 'kimono-stencil' for the first day, she pictures a design stenciled on the kimono. This picture recurs on the second day. On the third day, she thinks only of the words, design and stencil. On the fourth, fifth, and sixth days, the response, *stencil*, is immediate without any association or picture. These

examples show quite clearly how the associative connections between a stimulus and a response became shorter and shorter until finally the connection became immediate and direct, producing the shortest reaction time.

SUMMARY

Associative aids disappear with practice and condition the rate of improvement. They greatly facilitate the formation of new responses but delay those which have been mechanized. Psychologically their function is apperceptive, that is, they connect the old with the new terms and then disappear. Neurologically they seem to provide indirect conductive units of low resistance between newly stimulated neurones and serve to connect them directly by the shortest paths.

IV

We may think of this experiment as an experiment in the transfer of training in which the regular tests for the six days constituted the training series, and the *B*, *D*, and *U* tests as the test series by which the spread of improvement from the training series may be measured. Although there were no tests before training, we may assume that in the average the L.T'.s for the *B*, *D*, and *U* tests would have been the same as the L.T.'s of the regular tests on the first day. We may measure the spread of improvement in one way by the difference between the L.T.'s of the training and test series, and in another way by the number of correct responses without prompting in the *B*, *D*, and *U* tests. Since the former measure mixes up the pairs in which there was facilitation with those in which there was interference, we had better take the latter measure, for it keeps these two sorts separate. In the *B* tests the pairs were learned backwards, *i. e.*, the subjects named the first word as a response to the second word as a stimulus. The reaction time in the average is almost twice as long as for the regular tests on the sixth day. The frequency of associative aids is from two to six times as great. Or in comparison to the regular tests, the associative frequency as well as the L.T.'s in the *B* test compare favorably to what they were on the third day of the regular tests.

This means that learning a given pair of words *forwards* completely for *six* days will reduce the time for learning it *backwards* as much as three days of practice in the forward direction. Learning forwards then helps learning backwards. The reappearance of associative aids in the latter makes it probable that an association which aids learning in one direction also aids it in another. This is more clearly shown in the *D* and *U* tests, in which the influence of associative aids was studied more carefully. Table VIII shows that the L.T.'s for the *SB* and *RC* series are higher in the *D* and *U* tests than in the regular tests for the first day. According to this measure, although these pairs were learned in the same order every day for six days, the learners were yet unable to name the first words in either an *up* or *down* order. There were, however, some correct responses in these tests, averages of 3.55 and 4.16 in the *D* test for *SB* and *RC* series respectively, and averages of 2.70 and 2.78 in the *U* test for the same series. That is, learning the pairs forwards completely each day for six days enabled the learner to name little over one third of the first words of the pairs in a *down* order and a little less than one fourth of them in an *up* order. But the learning of the other words was so much longer than the average that time was lost in the *D* and *U* orders because of the six complete learnings in the forward direction. Learning the pairs in one connection therefore in some respects produced very great interference with learning them in another connection. But it also greatly facilitated the learning of some of them. The *WS* and *WP* series do not show this interference in the average L.T.'s. Their L.T.'s in the *D* and *U* tests are, however, higher than the average L.T.'s on the second day of the regular tests, but less than those on the first day, showing very little profit by the six complete learnings in the forward direction. The number of correct responses, however, is 4.86 for the *U* test in the *WS* series and 2.50 for the *D* test in the *WP* series. These successes can only be accounted for by assuming that the training gained by the six days' practice on the pairs in the forward direction was transferred to learning them in both the *up* and the *down* orders. The question now is, how shall

we explain this transfer? The answer again is found in the influence of associative aids. This was determined by calculating, on the one hand, the per cent. of the correct responses that were made possible or rather accompanied by a revival of some association established in the training series, and on the other hand, the per cent. of such successes due to guesses or perseveration. Table XI shows the results of the calculation for the respective series.

TABLE XI

SB						*RC*						*WS*			*WP*		
D			*U*			*D*			*U*			*U*			*D*		
NC	*% AA*	*% PSV*	*NC*	*% AA*	*% PSV*	*NC*	*% AA*	*% PSV*	*NC*	*% AA*	*% PSV*	*NC*	*% AA*	*% PSV*	*NC*	*% AA*	*% PSV*
45	91.1	6.6	29	79.3	6.9	73	87.6	4.1	18	94.4	5.6	112	83.9	5.3	80	85.0	6.3
N = 117			*N* = 99			*N* = 144			*N* = 72			*N* = 216			*N* = 252		

NC = the number of correct responses in the *D* or *U* tests.
%AA = % of these accompanied by associative aids.
%PSV = % of these due to guesses or perseveration.

It will be seen that from 84 to 91 per cent. of these successes are accompanied by a revival of former associations, from 4 to 7 per cent. of them appear to be mere guesses, and the small remainder are unexplained. The fact that such a high percentage of correct responses are preceded by associative aids suggests that the successes are possible through them. This will be made more evident by reproducing some examples from the records which are worthy of careful study. The following points should be noticed: (1) The rare frequency of successes which cannot be explained by a previously established association. (2) The absence or confusion of such associations in cases of failure. (3) The high frequency of successes connected with associations of order and position. (4) The absence of direct connections between stimulus and response. (5) The connection of the latter by a roundabout previously established associative path which was reexcited either in the same direction in which it was established or in

a reverse direction. (6) The formation of new associations where a success was not obtained without prompting.

In the examples below the stimuli are printed along the margin at the left in the order in which they were given. In the *D* test, the subject was asked to name the first word of the pair next to 'sauce,' mistake,' etc. The responses and the times are given opposite the pair containing the correct response. Immediately below this are given the associations which the subject had formed with these responses, the connection being indicated by the corresponding numbers. In the *U* test the subject was asked to name the first word of the pair before 'space,' 'kimono,' etc. The reader must bear in mind that in this test such terms as before, after, first, and last, when used by the subject have just the reverse meaning from that which would be indicated by their position on the page. This is because the stimuli in this paper are printed in the reverse order from that in which they were in the original sheets.

Miss Bov. April 22, 4–5 P.M. *D* test.

Sauce balloon:	
Mistake clean:	1. Elephant 3.4″. 2. Mistake 1.4″.
	2. Prompting reminded me that mistake follows sauce.
Elephant steeple:	1. Elephant 1.8″.
	1. If elephant is not second, it is third.
Simmer tarry:	1. Tomato 11.0″. 2. Simmer 3.6″.
	2. Remembered prompting.
Ring kitten:	1. No 6.6″. 2. Galley 1.4″. 3. Kitten 1.6″.
	3. Remembered prompting.
Turkey among:	1. Turkey 2.2″.
	1. Thought ring, kitten, among, turkey.
Chest muffin:	1. Chest 1.8″.
	1. Thought turkey, among, muffin, chest.
Galley time:	2. Kimono 10.6″. 2. Galley 2.2″.
	2. Remembered prompting.
Kimono stencil:	1. Kimono 2.2″.
	1. Kimono is next to last.
Space betide:	1. Space 1.2″.
	1. Space is last.

1. Miss Ber. 4–5 P.M. *D* test.

Sauce balloon:	
Elephant steeple:	1. Elephant 8.3″.
	1. Thought sauce-balloon steeple-elephant.

Ring kitten: 1. No 10.3″. 2. Ring 2.0″.
1. Thought of muffin-chest stencil kimono; these are not right, no.
2. Nothing.

Chest muffin: 1. Chest 5.0″.
3. Thought ring, muffin-chest.

Kimono stencil: 1. Kimono 2.6″.
1. Thought chest-muffin, stencil-kimono.

Mistake clean: 1. Simmer 4.0″. 2. Mistake 5.4″.
1. Thought kimono-stencil, tarry-simmer.
2. Remembered prompting. Saw objects for kimono-stencil but words only for mistake-clean.

Simmer tarry: 1. Simmer 2.0″.
1. Thought mistake-clean-simmer.

Turkey among: 1. Turkey 4.0″.
Saw simmer-tarry, among-turkey in order.

Galley time: 1. No 17.0″. 2. Galley 2.0″.
1. Saw the words turkey-among and time, but could not see galley.
2. Remembered prompting.

Space betide: 1. Space 2.3″.
1. Saw the words galley, time, betide, space.

Miss Wal. April 20, 3–4 P.M. *D* test.
Radish coffee:

Serve hold: 1. Serve 6.1″.
1. Serve hold is the second pair.

Pork cocoa: 1. Pork 2.2″.
1. Pork cocoa is next to serve hold.

Cheese tomato: 1. Cheese 2.3″.
1. Guessed it.

Speak weigh: 1. Speak 1.2″.
1. Had these arranged like this: First there was something to eat, and then there wasn't, then there was again, and then there wasn't again.

Ribbon banana: 1. 1. Celery 4.2″. 2. Being 8.6″. 3. Ribbon 1.0″.
3. Nothing.

Being credit: 1. Celery 2.4″. 2. Being 1.4″.
2. Guessed it.

Miss Bro. 3–4 P.M., June 1. *D* test.
Sauce balloon:

Elephant steeple: 1. No 16.2″. 2. Elephant 9.8″.
1. Only balloon.
2. Only elephant.

Ring kitten: 1. Ring 2.8″.
1. Thought it belonged here somewhere.

Chest muffin: 1. Turkey 3.0″. 2. Tarry 10.4″. 3. No 30.8″.
1. Turkey the only one in the list that I could think of.
2. Only simmer-tarry.
3. First didn't know whether elephant came before or after, concluded it came before, but could not think what was right.
4. Thought of elephant all the time, then thought it was something a kitten could eat, chest-muffin.

Galley time: 1. Galley 1.0″.
1. Guessed at it.

Kimono stencil: 1. No 7.5″. 2. Kimono 1.8″.
1. Nothing.
2. Guessed at it.

Miss Rie. 2–3 P.M. *U* test.
Geigen fiddle:

Citrone lemon: 1. Citrone 2.0″.
1. Thought of the last and the next to the last pairs.

Besonder particular: 1. Besonder 1.6″.
1. Thought citrone-lemon, besonder-particular, and knew that besonder came before citrone.

Angriff attack: 1. Angriff 1.7″.
1. Thought besonder-particular, Angriff-attack.

Ereignen happen: 1. Ereignen 1.7″.
1. Thought Angriff-attack; ereignen-happen.

Dach roof: 1. Körper 2.0″. 2. Dach 5.6″.
2. Thought ereignen-happen; dach-roof.

Anregen stimulate: 1. Stimulate 6.2″. 2. No 18.0″. 3. Anregen 1.2″.
3. Remembered prompting.

Körper body: 1. Körper 1.6″.
1. If Körper is not before eregnen, it is before anregen.

Beharren persevere: 1. Beharren 2.2″.
1. Thought Körper-body, persevere-beharren.

Wipfel-summit: 1. Wipfel: 1.7″.
1. Thought beharren-persevere, summit-wipfel, and that wipfel and beharren are the first and second words.

Mr. Kin. 5–6 P.M. *U* test.
Soup wall:

Troll blast: 1. No 6.0″. Troll 1.6″.
2. Remembered from prompting that they were the last and the next to the last pairs.

Celery wafer: 1. No 3.3″. 2. No 5.5″. 3. Lettuce 8.0″. 4. Celery 5.4″.
4. Saw celery and remembered prompting.

Being credit: 1. No 3.2″. 2. Being 2.7″.
2. Remembered prompting.

Ribbon banana: 1. No. 1.6″. 2. Lettuce 3.0″. 3. No 6.2″. 4. Ribbon 3″.
4. Remembered prompting.

Speak weigh: 1. No 4.8″. 2. No 2.4″. 3. Cheese 10.2″. 4. Speak 2.0″.
4. Remembered prompting. A fellow selling ribbon in a dry goods department and then saw Dept. filled with groceries, and saw a cheese on the counter, and beside the cheese there was a ham, and then I saw a girl from the refreshment department serving radishes.

Cheese tomato: 1. No 1.6″. 2. Cheese 2.3″.

Pork cocoa: 1. No 1.6″. 2. Pork 2.0″.

Serve hold: 1. No 1.8″. 2. serve 2.8″.

Radish coffee: 1. No 1.4″. Radish 1.4″.

Mt. T. 8–9 P.M., May 24. *U* test.
Geigen fiddle:

Besonder particular: 1. Ereignen 2.8″. 2. Besonder 1.0″.
1. Thought of Angriff and then ereignen.
2. Nothing.

Ereignen happen: 1. Ereignen 1.4″.
1. Nothing.

Anregen stimulate: 1. No 29.0″. 2. No 22.4″. 3. Anregen 3.6″.
1. Thought of stimulate but could not find the German.
2. Same.
3. Remembered prompting.

Beharren persevere: 1. Beharren 14.6″.
1. Thought of anregen-stimulate, and that persevere is before stimulate and goes with beharren.

Citrone lemon: 1. Angriff 17.0″. 2. Citrone 3.0″.
1. Had an image of the particulars of two words. Angriff is before beharren. There is something in between, but I could not find it.
2. Nothing.

Angriff attack: 1. Angriff 1.6″.
1. Nothing, knew from previous associations.

Dach roof: 1. Dach 6.6″.
1. First a blank, then I recalled that something was before. I started at the top of the list, found the place for each word, and when I came to this place, Dach occurred to me.

Körper body: 1. Körper 2.0″.
1. Suggested by previous association.

Wipfel summit: 1. Wipfel 2.8″.
1. Wipfel is first and Körper second.

The first example is from the *D* test with Miss Bov. E. pronounced the first word of the first pair, 'sauce.' The proper response is 'mistake,' but the actual one was 'elephant' with a reaction time of 3.4 seconds. After prompting, E.

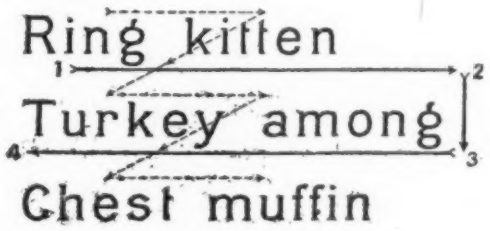
gave 'mistake' as a stimulus and obtained 'elephant,' the correct response. Subject's association was that if elephant did not come second, it came third. After E. went through the list in this way, he gave those stimuli again which were not correctly responded to the first time. He began with 'sauce' and obtained the correct response, 'mistake,' in 1.4 seconds. The previous prompting reminded the subject of the correct position of mistake. Miss Bov. has five successes in this test. Three of these are due to *associations of position.* Thus elephant is the third word, kimono is the next to the last, and space is last. The other two successes are due to *associations of order.* For example when she was asked to name the first word of the pair after 'turkey' she thought the words 'turkey,' 'among,' 'muffin,' 'chest,' and then said 'chest.'

The above two types of association explain most of the successes in the *D* tests. Words near or at the ends were associated with absolute position and those in the middle with the order of learning. There are a few instances, however, in which the order of the pairs was connected with meaningful associations. For example, Miss Wal. had the first five pairs of the *RC* series connected with the story. "First there was something to eat, and then there wasn't again, and then there was again, and then there wasn't again." Some had scarcely any association of position or order, and the *D* test presented a case of learning a new series. The first record from Miss Bro. is a case in point.

The *U* tests show only one important difference in the associations by which the successes were obtained, namely, that they are worked out in the reverse order from that followed in learning. For example, when Mr. T. was told: "Name the first word of the pair that comes before 'anregen'" he replied correctly, 'beharren,' with a reaction time of 14.6″. The association was: "I thought of 'anregen-stimulate,' and that 'persevere' is before 'stimulate' and goes with 'beharren.'" The associations of absolute position are just as frequent as in the *D* test. A few subjects showed pronounced visual imagery in this test, *e. g.*, when Miss Ber. was asked to name

the word before 'Angriff,' she reported that she saw a 'Dach' above it and the third from the top. The second record from Miss Bro. is an example of a subject who had few successes in the *U* test, and who had to form a set of new associations in order to learn the pairs in this order.

Although not all of the pairs fall within the category of order and position, the latter are the only ones of importance. The diagram given below will serve as a basis for discussing these associations. A success in the *D* test depended on a definite association both from 1 to 4. A success in the *U* test depended on the ability to travel the path from 4 to 1. A success in the *B* test depended on the ability to travel the path from 2 to 1. Most frequently the path extended only from 1 to 2. Sometimes it extended in addition to 3, and the subject named the word at 3 but was unable to think of the word at 4. Sometimes the path extended only between 2 and 3 and between 3 and 4, enabling the learner to travel from 4 to 3 but no farther. It is important to mention these incomplete paths because they explain the failures in the *D* and *U* tests just as the complete paths explain the successes.



The great frequency of the associative path designated by the solid lines gives rise to the question why the subject did not associate the pairs in the order of presentation as is indicated by the broken lines. At first thought it would appear that the latter would also be the order of the learning. The solid line arrows, however, indicate the direction in which the subject *thought* them and *reacted* to and with them. For the subject to think: "After 'kitten,' I say 'among' to 'turkey' and then 'muffin' to 'chest'" was a simpler order

then to think: "After 'kitten' comes 'turkey' to which I say 'among' and then comes 'chest' to which I say 'muffin'." There are cases of the latter order, but they are much rarer than the former. It appears here that the order of *thinking* and *reacting* is much more important for establishing an associative path than the order of presentation. In spite of the fact that E. said the first words in the same order many times, day after day, the learner after all did not establish any association in that order nor achieve any successes in the *D* and *U* tests by such associations. The order of *listening* counted for little in comparison to the order of *responding*.

This emphasizes the importance of selective activity on the part of the learner in the formation of associations and leads me to a digression on the law of contiguity, which appears to be at variance with the facts of experience. The mere togetherness of two presentations in space or time is no proof that they will be associated. If it were, there should have been few failures in the *D* and *U* tests, for the frequency of the connection 1–2, was hardly any greater than that of the connection, 1–2–4, in the above diagram. Yet the subject, on the sixth day, remembered the former connection in over 95 per cent. of the cases, but in the latter he failed in 66 per cent. of the cases. This is striking proof that the frequency of contiguous presentations is not alone sufficient to establish an association between them. Some factors determining this situation were: The subject was interested in the connection, 1–2, it was exercised, and its exercise was satisfactory. The subject was not interested in the connection 1–2–4, and it was not exercised although it was objectively presented. But of these, the most important factor is probably exercise. From a neurological standpoint, it is not at all certain that the presentation of an object to a learner stimulates his sense organs, and if it does, it is again not certain that it stimulates a complete sensory-motor arc. Even if the latter does occur, the exercise of the bond in question may be so feeble as to leave no after-effect. But whatever the explanation of the failure may be, it at least appears from the results of this

experiment that only those experiences to which we definitely react are associated. The following formula of the law of contiguity is therefore suggested: If a learner reacts to *A* and *B* together in some experience, and if later he again responds to one of them, the former reaction to both of them tends to follow; or stated more simply, if a learner reacts with *A* to *B* and if later *B* recurs, *A* tends to follow. In this connection I am reminded of Hunter's revision of the law of association in the PSYCHOLOGICAL REVIEW, May 1917. While I agree that the second term of an association may be either sensory or ideational, I do not think that the failure to recognize this is the fundamental weakness of the traditional formulation. Its weakness is rather that it emphasizes the togetherness of an experience that is important in the establishing of an association. But as we have seen, this is of little importance in comparison to a positive reaction to the experience for the purpose in question.

Coming now to the main question at issue in these *D* and *U* tests, the explanation of the transfer of training, it appears from the above results that learning one thing helps to learn another only in so far as the associations which were established in the first can be made use of in the second. It is clear from the results of this experiment that learning things in one direction helps to learn them in another, that is, when two or more objects are learned well enough in one direction, it is possible at another time to recall these objects in a new order; but, if so, the objects in question must have been connected by some *actual* association *between* them. If association explains the transfer of training, it also should explain the variability in the amount of transfer between one individual and another. That this is the case is evident from Table XII., which shows that the number of correct responses in the *D* and *U* tests varies concomitantly with the number accompanied and preceded by associative aids. Now and then there is an exception which is easily explained by perseveration or a possible forgetting of the association in question. But the correspondence is so close that the main conclusion is inevitable.

TABLE XII

SB								RC								WS				WP			
D				U				D				U				U				D			
S	NC	NA	PSV	S	NC	NA	PSV	S	NC	NA	PSV	S	NC	NA	PSV	S	NC	NA	PSV	S	NC	NA	PSV
Joe	7	7		Fac	5	4		Fra	8	8		Ber	4	3	1	Jen	9	9		Gib	6	5	
Ber	6	6		Jen	4	4	1	Sin	7	7		Ham	4	4		Tra	8	5		Pfe	6	3	
Gre	6	5	1	Tra	4	2		Wol	7	5		Joe	4	4		Ber	7	7		Bov	5	4	
Bov	5	5		Wal	4	4		Gib	6	5		Pan	4	4		Fac	7	5		Gre	5	4	1
Kel	4	4		Dav	2	2		Jen	6	5	1	Hil	2	2		Joe	7	7		Sul	5	5	
Ham	3	3		Hof	2	1		Pfe	6	6		Kel	0	0		Pfe	7	3	1	Bro	4	2	2
Hil	3	3		Huf	2	1	1	Tra	6	6		Rip	0	0		Rie	7	7		Huf	4	3	
Pip	3	2	1	Sul	2	2		Dew	5	4		Wic	0	0		Bov	6	4	1	Pan	4	4	
Bro	2	1	1	Swa	2	2		Eva	5	4						Eva	6	6		Bor	3	3	
Kin	2	1		Pfe	1	1		Rie	5	4						Pan	6	5	1	Dav	3	3	
Pan	2	2		Rie	0	0		Teh	4	4						Teh	6	6		Eva	3	3	
Woo	2	2						Bor	2	0						Bor	5	5		Fac	3	2	
Wic	0	0						Hof	2	2						Bro	5	4	1	Huf	3	3	
								Huf	2	2						Ham	4	3	1	Kel	3	3	
								Woo	2	2						Hil	4	4		Teh	3	3	
								Swa	0	0						Huf	4	3		Wall	3	2	1
																Kel	4	4		Woo	3	3	
																Tra	4	3		Ber	2	2	
																Woo	4	3		Ham	2	2	
																Gre	2	1	1	Hof	2	2	
																Kin	0	0		Joe	2	2	
																Rip	0	0		Wic	2	2	
																Swa	0	0		Hil	1	0	1
																Wic	0	0		Pip	1	1	
																				Swa	1	1	
																				Tra	1	1	
																				Kin	0	0	
																				Rie	0	0	

S = Subject.
NC = No. of correct responses.
NA = No. of correct responses having associative aids.
PSV = No. of correct responses apparently due to perseveration.

The training and the tests of this experiment are not sufficiently varied to prove conclusively that associative bonds are the only factors which determine the extent, limit, and possibility of the spread of improvement. But we can test the validity of this theory to a certain extent by examining how far it appears to be adequate for explaining the results obtained by other investigations in this field.

If the transfer of training takes place by means of common associative bonds, then the explanation of this phenomenon is simply a case of bringing it under the laws of association. Theoretically the problem with the experiments

on the transfer of training is to find in them illustrations of the laws of association. If the mind is primarily a psychophysical mechanism for reaction, then common associative bonds may occur either through identity and similarity in the stimulus or through identity or similarity in the response. The stimulus may be either sensory or conceptual and the response may either be conceptual or overt. Training may then be transferred from one performance to another when the two have (1) common sensory stimuli; (2) common conceptual stimuli; (3) common overt responses; (4) common conceptual responses.

It may be difficult to bring all the reported cases of the transfer of training under the above categories, but it appears that most of the authentic cases of transfer or of its failure can be so classified.

The following cases of positive transfer may be noticed: When there is transfer of training from estimating areas 10–100 sq. cm. in size to estimating areas 10–250 sq. cm. in size in proportion as the size of the latter approach the size of the former, there appears to be a common response because of similarity in size. When training in cancelling words with e and s is transferred to cancelling words with e and r, or s and p more than it is to cancelling misspelled words or to cancelling capital A's mixed up with a number of other capitals, there is again a common response to the extent that there is a common sensory stimulus in the letters or small geometrical forms in a certain order.[1] When practice in typewriting certain visual stimuli in one order improves the ability to typewrite them in another order, there are common sensory stimuli in small letters appearing at the same place and in a certain order and in the feel of the keys. There are also common responses in the eye movement from copy to keys and in the finger movements to the particular visual stimuli.[2] Transfer from improvement in discriminating intensities of red to discriminating intensities of mixtures of yellow and

[1] Thorndike and Woodworth, PSYCHOL. REV., 1901, 8, 247–261; 384–395; 553–564.

[2] Bair, J. H., PSYCHOL. MONOG., No. 19, 1902.

green, intensities of orange, and differences in pitch, is a case of common response by careful observation of small differences. That there is more transfer between small differences within the same modality than there is between those in different modalities again shows the influence of the extent of similarity in the stimulus. Transfer from training in reproduction of one order of four intensities of sound after hearing them in another order to similarly arranged reproductions of the order of four grays, four tones, nine grays, nine tones, nine geometrical figures, two stanzas, and nine numbers—involves common sensory stimuli in separating out order and in the arrangement of stimuli; a common conceptual stimulus in 'Remember one order while perceiving another'; a common conceptual response in associating the stimuli in a certain order; and a common overt response in naming them in a certain order.[1] The order in which the test series were named above shows the extent of the improvement from most to least, and this again shows the importance of the extent of the similarity in the stimulus in number, quantity, or span. Transfer of training in descriptive geometry in amount from most to least to ability to name the number of lines necessary to construct various geometrical objects, to state the number of strokes necessary to write certain words in the straight-line alphabet, to divide mentally three-place numbers by one-place numbers, to state the number of one-inch cubes in a three-inch painted cube which have 0, 1, 2, and 3 painted sides respectively, and to write as many words as possible from the letters in 'material,' is a case that invokes a common sensory stimulus in spatial elements; a common conceptual stimulus in 'Separate them out, hold them apart and put them together'; and a common conceptual response in the mental manipulation and association of spatial elements.[2] The influence of a common stimulus is again evident here because there is more transfer to geometrical objects than to quasi-geometrical objects and more to the latter than

[1] Fracker, G. C., PSYCHOL. MONOG., No. 38, 1908, 56–102.

[2] Rugg, H., 'The Experimental Determination of Mental Discipline in School Studies,' 1916.

to non-geometrical objects. Transfer of training from learning nonsense syllables by one method to learning them by another method involves common sensory stimuli in similar material; a common conceptual stimulus in 'Learn them as soon as possible'; and common conceptual responses in the form of association and reproduction.[1] Transfer from neatness in one school subject to neatness in another school subject is a case of responding to the common[2] conceptual stimulus 'Be neat.'

Certain cases of failure in transfer of training are equally significant for the theory stated above. The following may be noticed.

Training in card sorting does not improve ability to typewrite. Training in estimating areas 10–100 sq. cm. does not improve ability to estimate similar areas over 200 sq. cm. in size. Training in estimating lines .5 to 1.5 inches long does not improve ability to estimate objects from 2.5 to 8.75 inches long when the latter consist of such things as envelopes, brushes, and wrenches. Training in estimating four intensities of sound does not improve ability to estimate the extent of arm movement. Training in cancelling parts of speech does not improve ability to cancel words having the letters e and t.[3] Training in memorizing 'Paradise Lost' does not improve the memory for Hugo's verse.[4] Training in memorizing nonsense syllables does not increase the memory-span for letters, numbers, nonsense syllables, disconnected words, Latin-English vocabularies, poetry, and prose; nor the ability to memorize completely meaningless visual characters, Latin-English vocabularies, and passages of poetry and of prose.[5] Training in memorizing prose substance does not improve the ability to memorize dates, nonsense syllables, poetry, points on a map, dictation, letters, and names. Training in memorizing tables does not improve ability to memorize

[1] Reed, H. B., 'Repetition of Ebert and Meumann's Practice Experiment in Memory,' J. of Exp. Psychol., 1917, 2, p. 315.

[2] Reudiger, W. C., *Educ. Rev.*, 1908, 36, p. 364.

[3] Kline, L. W., *J. of Educ. Psych.*, May, 1914.

[4] James, W., 'Principles of Psychology,' 1890, Vol. 2, p. 67.

[5] Reed, H. B., J. of Exp. Psychol., 1917, 2, 315ff.

dates, poetry, prose, prose substance, dictation, letters, and names. Memorizing poetry does not improve ability to memorize dates, poetry of another sort, prose, prose substance, points on a map, dictation, letters, and names.[1]

I have also examined the results of experiments on the transfer of training by Bagley and Squire,[2] Briggs,[3] Burnet,[4] Coover,[5] Dallenbach,[6] W. F. Dearborn,[7] Foster,[8] Hewins,[9] Judd,[10] Ruger,[11] Scholkow and Judd,[12] Wallin,[13] Whipple,[14] and Winch,[15] but have not been able to make them the basis of a theoretical discussion because they were too indefinite, irregular, or complicated to bring within a consistent rule. However, no theory that is at all specific can explain all cases of reported transfer. The psychological factors in the cases of positive transfer described above were pointed out. In the cases of negative or zero transfer it is difficult to find common sensory stimuli, and common conceptual stimuli that may exist are too general to be effective. It is also difficult to find common conceptual or associative responses. But some cases of positive transfer are equally baffling; for example, training in memorizing poetry has been found to improve the ability to locate points on a map and to memorize nonsense syllables, but interfered with the ability to learn poetry of another sort, prose, or prose substance. Memorizing tables improved the ability to locate points in a circle and to learn nonsense syllables, but interfered with the ability

[1] Sleight, W. G., *British J. of Psych.*, 1911, 4, 386–457.

[2] Bagley, W. C., 'Educational Values,' 1905, p. 188 ff.

[3] *Teachers College Record*, Sept., 1913.

[4] 'Formal Discipline,' Columbia University Contributions to Education, 1907.

[5] Psychol. Monog., No. 87, 1916.

[6] *J. of Educ. Psychol.*, 1914, 5.

[7] *J. of Educ. Psychol.*, 1911, 1, 386–457.

[8] *J. of Educ. Psychol.*, 1911, 2, 11–21.

[9] 'The Doctrine of Formal Discipline in the Light of Experimental Investigation,' 1916.

[10] Psychol. Rev., 1902, 9, 27–39.

[11] 'Psychology of Efficiency,' *Archives of Psychology*, No. 15.

[12] *Educ. Review*, 1908, 36, 28–42.

[13] 'Spelling Efficiency in its relation to age, sex, and grade,' *Educ. Psychol. Monographs*, 1911.

[14] *J. of Educ. Psychol.*, 1910, 1, 249–262.

[15] *British J. of Psychology*, 1908, 2, 284–293.

to learn dates, poetry, or prose. The difficulty with all these studies is that the associative processes were not investigated. If we knew what the common bonds of association had been in these cases of positive and negative transfer, we probably should have the cue to their explanation. The correlation between observable stimuli and observable responses is too irregular to make a consistent principle inferable with certainty, but such regular correlations as there are point quite definitely to the solution of the problem in the laws of association. It is to be hoped that future investigators of this problem will more carefully examine the internal facts of transfer, *i. e.*, the common associative bonds.

The above theory does not contradict Thorndike's theory of identical elements. It simply makes it more specific and states that these identical elements consist of associations. The difficulty with the theory of identical elements is the indefiniteness of its meaning. At first it meant principally identity of content but later was extended to identity of procedure and identity of neurological process, but these again are terms of no specific meaning. The wide latitude of the meaning of identical elements is clearly shown by Coover who, both by observation and by introspection, found no less than "40 varieties" of the identical element between one process and another. But the scientific problem with them is to show in verifiable, quantitative evidence which of those forty factors are important and which are not important. That an element is common between two processes tells us nothing about how much one process influences another process unless there is concomitant variation between the amount of this influence and the amount of the common factor.

An examination of Coover's results from this standpoint brings disappointment. His results were recently reported in a three hundred-page monograph. Space prevents me from reviewing it, but if the reader will turn to the sections on "Card-sorting" and "Typewriter reaction," pages 118–131, he will get an idea of Coover's method. He finds no less than "twenty varieties" of the card-sorting process.

When he gives the results on the amount of transfer by various subjects in visual apprehension, sound reaction, and mnemonic devices upon the card-sorting reaction, he finds a residual gain of 10 per cent. on the part of the eight trained subjects. But there were only two controls and these gained as much as two of the trained, and a good deal more than one of them. How then can he be certain that the 10 per cent. greater gain by the other five subjects is not a matter of accidental variation? As an explanation of this very uncertain transfer, he offers the following factors: heightened sensitivity for visual impressions, heightened reproductivity of imagery, coördination of part-processes, exercise of continuous attention and reproduction of memorial elements and habituation to distraction. But he offers not an iota of quantitative evidence that any of these factors are important for improvement or for transfer. If these hypothetical factors are of any importance in either connection, we should have some scientific and objective evidence as a ground for our judgment, *e. g.*, some constant connection or concomitant variation ought to be shown between any of these factors and improvement or transfer. Unless an investigator can produce such evidence, his results only multiply the difficulties of the problem in question.

Summary

In this experiment evidence that learning things in one order helps to learn them in different orders is considered proof of transfer of training. Such transfer takes place through the use of associative bonds common to the old and new orders. Such a use is essentially a case of thinking through old associations in new directions.

The evidence for the theory that transfer of training must be explained by common associative bonds is contained in Tables XI and XII. The former shows that from 84 to 94 per cent. of the cases of transfer are accompanied by associative aids and the latter shows a concomitant variation between the number of cases of transfer and the number of associative aids. On these grounds a causal relation is assumed.

Further evidence for the theory is furnished by an examination of the literature of the clearest cases of transfer. If associative bonds are the media of transfer, then the explanation of these cases is simply a problem of bringing them under the laws of association. This would mean that training may be transferred from one performance to another when the two have (1) common sensory stimuli; (2) common conceptual stimuli; (3) common overt responses; (4) common conceptual responses. An attempt to explain the clearest cases of transfer by these principles appears reasonably successful.

The above theory does not contradict Thorndike's theory of identical elements, but simply gives it a specific meaning. It also insists that identical elements cannot be assumed to be media of transfer unless the quantitative proof for them is clear.

Incidentally the experiment demands a reformulation of the law of contiguity. The togetherness of objects in experience is not a sufficient condition of association unless it is accompanied by active attention.

INTELLIGENCE AS ESTIMATED FROM PHOTOGRAPHS

BY RUDOLF PINTNER

Ohio State University

There is a widespread belief that it is a relatively simple thing to estimate a person's intelligence after a perfunctory conversation with him or even merely by looking at him. One hears again and again the expressions, 'he looks bright,' and 'he looks stupid.' Such judgments of intelligence are most often made in regard to children. Teachers have a very firm belief in their own ability to judge the intelligence of their pupils, in spite of the fact that correlations of their estimates with the results of mental examinations have been shown to be decidedly low. Physicians are also very prone to make snap-judgments of people and, because of their personal contact with a large number of people of all classes, they come to believe tremendously in their own ability in this direction. The physician, of course, is not primarily judging intelligence, in the narrow sphere of the psychologist's definition. He is judging rather that larger and vaguer thing we call 'character.' Neither the physician, however, nor the teacher hesitate for a moment in judging the intelligence of individuals, if challenged. Indeed, they do not appear to think it more difficult to judge intelligence pure and simple than to judge 'character.' There is, however, a group of physicians who are daily passing judgment in regard to the intelligence of individuals. This group includes the psychiatrists, the physicians in institutions for the feeble-minded and some others who happen by chance to be repeatedly called in to a probate court to pass upon cases of suspected insanity and feeble-mindedness. Most of these believe thoroughly that that magical thing known as 'experience' has endowed them with the gift of estimating the intelligence of a case after a brief interview, in which appear certain

stock questions about the President of the United States, and so forth. Most of them scorn any assistance that mental tests may give them.

Because there are many practical difficulties in obtaining the judgments of a number of individuals in regard to the intelligence of the same group of children, we have substituted photographs for the living child. This substitution, of course, makes the problem more difficult. It is much harder to make a judgment of intelligence about a photograph than about the living child. Whether the judgments in the latter case would be more accurate has not been investigated. The presumption is, of course, that they would be, because the movements and the language of the child give us added data from which to draw a conclusion as to his intelligence.

In this investigation twelve photographs of children of varying ages were used. All of these children had been tested by the writer on the Yerkes-Bridges Scale. The photographs are shown on the following pages, and under each child the chronological age, the mental age, and the coefficient of mental ability are given. The pictures of children are arranged in the order of intelligence as determined by the C.M.A., reading from left to right and downwards. Of the children Nos. 1 and 2 would be classed as very bright; No. 3 as bright; Nos. 4, 5 and 6 as normal; Nos. 7, 8 and 9 as backward; and Nos. 10, 11 and 12 as feeble-minded. In fact the three feeble-minded children are at present inmates of a feeble-minded institution.

The observers were asked to arrange the twelve photographs in the order of their intelligence, beginning with the most intelligent child. The ranking according to the observer was correlated with the ranking according to the mental examination, the formula

$$\rho = 1 - \frac{6 \Sigma D^2}{n (n^2 - 1)}$$

being used.

The observers have been grouped into four classes, namely, 9 physicians, 15 psychologists, 11 miscellaneous, 11 students and 17 teachers. The group of physicians was made up of two general practitioners, one tuberculosis special-

ist, one skin specialist, one anæsthetist, one physical director of a large public-school system, and three physicians employed in institutions for feeble-minded. Of the group of 15 psychologists, all except one had had experience in giving mental tests. Seven were devoting most of their time to clinical or abnormal psychology. Four were graduate students or assistants specializing in mental tests. Of the 11 miscellaneous people, three were business men, one was a married woman, and seven were stenographers. The group of 11 students was part of a class studying the problems of feeble-mindedness and the measurement of mentality. All of them had attended clinics throughout the semester, in which all types of defectives were shown, and many of the students had had some limited experience with mental testing. The group of 17 teachers was a summer-school class in mental measurements made up of teachers and superintendents. A few of these had had experience in the giving of mental tests. All our groups, therefore, with the exception of the miscellaneous group, had been brought face to face with the definite problem of the differences of intelligence that exist in children. The miscellaneous group had never had this problem brought to their attention and it is doubtful whether there existed in their minds any very definite idea as to the meaning of the term 'intelligence,' and no academic definition was given them before they were asked to arrange the photographs. Although several of the observers remarked on the difficulty of the experiment, none paused because of any difficulty about the meaning of intelligence. As a rule, very little hesitation was shown by the observers in making their decisions.

The correlations of the observers arranged according to these groups are given in Table I. Minus signs are inserted before negative coefficients; plus signs have been omitted. The coefficients are arranged in order of size. The first column gives the coefficients of the physicians, and is to be interpreted as follows: The first physician, who made the highest coefficient, had a coefficient of +.28; the next physician of +.25, and so on down to the negative coefficient of

−.21 of the last physician. The row, marked '*n*' at the bottom of the table gives the number of individuals in each group. The next row, marked 'Av. *r*,' gives the average of the coefficients for each group. The next row, marked

TABLE I

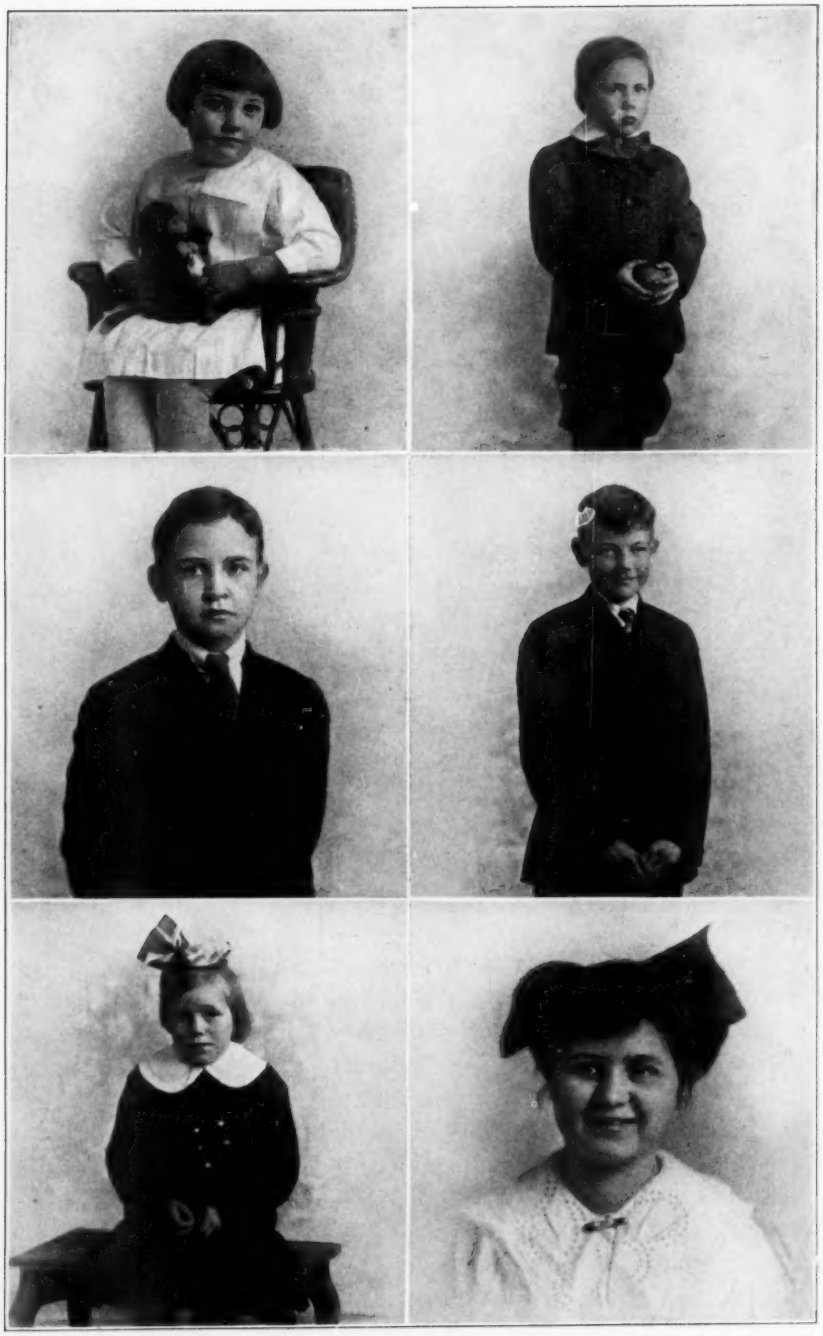
DISTRIBUTION OF COEFFICIENTS OF CORRELATION

	Physicians	Psychologists	Miscellaneous	Students	Teachers
	28	45	52	29	37
	25	41	39	27	34
	21	40	31	24	33
	19	38	14	15	27
	04	34	09	06	27
	−08	33	01	03	24
	−10	31	01	−06	15
	−14	27	01	−07	13
	−21	15	−19	−08	10
		13	−32	−24	08
		−01	−51	−30	08
		−02			06
		−09			−05
		−63			−07
					−26
					−28
					−29
n.....	9	15	11	11	17
Av. *r*.....	+.05	+.18	+.05	+.03	+.09
Av. rank *r*....	+.11	+.31	+.06	+.03	+.17

Median *r* for all cases = + .10.

'Av. rank *r*,' gives the correlation between the ranking of the twelve photographs as determined by the whole group and the ranking as determined by the mental examination. The median coefficient for all the 63 observers is +.10.

An examination of the coefficients of each group is interesting. The highest coefficient among the physicians is made by one of the general practitioners, who had some interest in mental tests. The three institution physicians made coefficients of +.04, −.08 and −.10, or, on the average, lower than the average of the other six physicians. The average for all the physicians is +.05. It would seem, therefore, that this group of observers is not able to arrange the photographs according to intelligence. Their average arrangement is about what might be expected from a chance arrangement of the cards.



No. 1.	Chron. Age 4.	M. A. 5.7.	C. M. A. 1.93
No. 2.	Chron. Age 5.	M. A. 7.2.	C. M. A. 1.64
No. 3.	Chron. Age 10.	M. A. 12.	C. M. A. 1.21
No. 4.	Chron. Age 10.	M. A. 10.8.	C. M. A. 1.09
No. 5.	Chron. Age 7.	M. A. 6.8.	C. M. A. .97
No. 6.	Chron. Age 16.	M. A. 12.5.	C. M. A. .90

No. 7.	Chron. Age 10.	M. A. 9.	C. M. A.	.88
No. 8.	Chron. Age 12.	M. A. 9.7.	C. M. A.	.81
No. 9.	Chron. Age 12.	M. A. 10.	C. M. A.	.80
No. 10.	Chron. Age 15.	M. A. 9.8.	C. M. A.	.72
No. 11.	Chron. Age 12.	M. A. 8.6.	C. M. A.	.72
No. 12.	Chron. Age 14.	M. A. 7.6.	C. M. A.	.47

Among the psychologists there are three coefficients above 40 and seven above 30. All of these are low, but they denote some measure of agreement. But, on the other hand, there are four negative coefficients and one, $r = -.63$, the largest negative coefficient in the whole table. This coefficient was made by a psychologist whose particular interest is abnormal psychology. The highest coefficient, $r = .45$, is also made by a psychologist whose chief interest is abnormal psychology and who has had varied experience in mental survey work. The seven psychologists who have had much experience in mental tests made coefficients of 45, 41, 38, 13, −02, −09, −63. The wide variation in these coefficients shows that experience in mental testing is no guarantee of ability to judge intelligence as shown in the photographs of people. Taking the psychologists as a group, we note that the average r is +.18. The average rank of the children obtained from all the psychologists' rankings gives a correlation of +.31 with the real arrangement. This coefficient is high enough to indicate a measure of agreement beyond mere chance. However, it takes the average ranking of 15 psychologists to obtain this correlation. If the large negative coefficient of −.63 be omitted, the average of the 14 remaining coefficients is +.22. If the observer who made this high negative coefficient had not been a clinical psychologist, a fair average for the clinical psychologists might have been obtained, but as it is, it would seem as if the clinical psychologist is just as likely to err in his judgment of intelligence by means of photographs as is any other individual.

In the miscellaneous group is to be found the highest single coefficient, namely +.52, and this was made by a stenographer. It would seem as if a business training in shorthand and typewriting is just as useful in training us to be good judges of the intelligence as expressed in people's photographs, as is a study of medicine or a Ph.D. in psychology. In this same group, besides the highest positive coefficient, there is also the second largest negative coefficient, $r = -.51$, made by a business man. The average of the coefficients is +.05, the same as the physicians' average.

There is nothing of note in the coefficients of the students. They range from +.24 to −.30, showing a very normal distribution. Their average is +.03, the lowest average for any of the groups.

The coefficients of the teachers' group range from +.37 to −.29 and also show a fairly normal distribution. The average of the coefficients is +.09.

Ten chance arrangements of the photographs were made and the rankings correlated with the ranking according to the mental tests. The average of the coefficients is −.08, and the coefficients range from +.43 to −.74. Except for the high negative coefficient of −.74, the chance coefficients are just about as good as those of the observers in general.

All the four groups show a very small average coefficient. That of the psychologists is the highest, but is not sufficiently high to denote any great degree of resemblance between the rankings. The median r for all the 63 individuals who performed the experiment is +.10. On the whole, therefore, we may say that it is impossible by means of photographs to rank children according to their intelligence. Some of the high correlations that were obtained are probably due to chance. This is suggested by the fact that the psychologist who made a coefficient of +.45 only succeeded in making a coefficient of +.28 when ranking the photographs a second time about six months after the first trial. That his judgment of the children remained fairly constant is shown by a coefficient of +.76 between his two arrangements.

It is interesting to note that there was a fairly close agreement between the average ranking of the children for the four groups of observers. The average rank of each of the twelve children for each group of observers was calculated, and these rankings were correlated with the final ranking obtained from all the 63 observers. The coefficients for the five groups of observers are .91, .94, .84, .89 and .92 respectively. This shows a fairly close agreement among the judgments of the observers as a whole. The correlation of the ranking as determined by all the observers with the true ranking is +.16.

Table II. shows the rank according to the mental tests, the rank according to the 63 observers, obtained from the average rank, which is given in the next column, and finally the average deviation. The average deviation gives us a measure of the difference of opinion among the observers as to the rank of the child. The smallest A.D. is 1.5 for child No. 3. This child is given first place more frequently than any other child, and there is the least difference of opinion

TABLE II

RANKING OF CHILDREN BY ALL OBSERVERS

Child No.	Rank	Av. Rank	A. D.
1.	4	5.2	2.3
2.	9.5	8.9	2.1
3.	1	2.7	1.5
4.	5	5.2	2.3
5.	11	9.4	1.7
6.	6	5.4	2.3
7.	3	4.9	2.2
8.	12	9.7	2.0
9.	7	5.9	2.4
10.	9.5	8.9	2.1
11.	2	3.3	2.3
12.	8	7.5	2.1

about him. Child No. 3 shows the thoughtful and serious aspect that is commonly associated with superior intelligence. The tests show him to rank third and he would be classed somewhat above normal, as a bright boy. The next two smallest average deviations are those of children Nos. 5 and 8, the two who receive the lowest average rank. The observers as a whole differ least as to which they consider the brightest child and which the two least intelligent. No. 5 was repeatedly called 'stupid' and often 'imbecilic,' and some observers pointed to the position of the hands as suggesting the picking of the fingers seen sometimes in idiots. No. 5 is, as a matter of fact, a perfectly normal child. No. 8 was called 'wild' and 'silly' and receives the lowest ranking according to our observers. By the mental tests she would be considered a backward, but not feeble-minded child. The largest average deviation is that of child No. 9. According to the tests he ranks ninth and would be classed as

backward but not feeble-minded. The average rank of the observers places him seventh. Many observers place him low because of his rather expressionless face, but the large average deviation is caused by a few observers who place him very high. Although this was never openly acknowledged, the writer suspects that in some of these cases the observers were influenced by his glasses and placed him high because of the intelligence conveyed by those useful adornments.

Comparing the rank obtained by the observers as a group in column two with the rank according to the mental tests in column one, we note that the greatest divergence occurs in child No. 11, who is ranked second by our observers. This child has the sparkling eyes and bright face that conforms so well with our popular conception of 'brightness,' and yet she is an inmate of a feeble-minded institution. The next greatest divergence is in child No. 2, who is ranked 9.5 by our observers. He is a very bright boy, according to the tests, and yet his expressionless face and rather awkward pose is interpreted as intellectual dullness by the observer. The tests and the observers both agree in placing child No. 6 about the middle of the group. There is also a close agreement with regard to child No. 10, whose fat expressionless face is taken to be indicative of a lack of intelligence. Child No. 4 is placed fifth by our observers, although what was regarded as a silly smile by some led them to rank him low.

It is impossible to analyze out of all the opinions of the observers any single factor or set of factors which seem to guide us in our judgments of intelligence when confronted with pictures. Some observers seem to look at nothing in particular and make their judgments in a hap-hazard fashion, while others will draw the most definite conclusions from slight hints suggested by the hands or face or clothes of the child, and in most cases it would seem as if such conclusions are as likely to be false as they are to be true. Some are greatly influenced by the pleasant appearance or smile, but for some the smile denotes intelligence and for others it denotes feeble-mindedness. The position of the hands is all-

important to one observer, and, if the feet had been showing on all the pictures, it is probable that they would have been of diagnostic value for some observer. Several observers confessed being greatly influenced by the resemblance of some of the photographs to children of their acquaintance, and it is doubtless true that everyone is influenced in this way, consciously or unconsciously.

It is the writer's opinion that the trivial things mentioned here are at work in the snap judgments that we make of people in everyday life, and that they are also at work, perhaps to a lesser degree, in the judgments of children made by teachers, physicians and psychologists, who do not use mental tests for purpose of mental diagnosis. The writer does not believe that the correlations would have been very different, if the actual children could have been used instead of the photographs. They would have been somewhat higher, if an interview of five minutes had been allowed with each child. They would only become very high when each observer makes use of some objective criterion or test.

THE GENESIS OF THE IMAGE

BY CURT ROSENOW

University of Chicago

In this year of grace, the doctrine that imagery arises at times when other more habitual psycho-physical processes are unable to deal with a problematic situation is scarcely in need of defense. Nor is it my purpose, in the present article, to rush to the aid of the victor, at any rate not without endeavoring to show that he is in need of assistance. For I wish to point out that a doctrine which is capable of being expressed only in terms as vague as the above is an article of faith rather than a scientific explanation. Unless we wish to call a day dream a problematic situation we must admit that, as a matter of fact, imagery arises in profusion at other times also, so that the appeal of the doctrine seems to be based less on factual verification than upon the way in which it fits in with the developmental, genetic point of view. If so, it would seem incumbent upon the defenders of the faith to state their case in intelligible fashion. If the doctrine does not describe the facts of adult life correctly, it should at least give us, as precisely and concretely as possible, the hypothetical conditions which would tend to make the genesis of the image appear if not the necessary result, at least a plausible and intelligible consequence of such conditions. And yet, when I let my mental gaze wander over the relevant literature of the past two decades, I am unable to find anything like such a description.

Take for example the way Angell states the case: "In seeking to detect the appearance—of imagery we must remember that from the outset of life organic activities are in progress and the sensory motor activities in particular are in full swing. Each sensory stimulus is producing movements, which in turn are productive of fresh sensations. It is out

from such a cycle of onward-moving coördinations as these that the image emerges; and—it must be that the image is called forth by some need of the organism which the processes that we have already described are incompetent to satisfy."[1] But the existence of *some need of the organism* is not, alas, a guarantee of its satisfaction. If I feel the desire to fly, that does not imply that I will at once proceed to sprout wings.[2]

Nor can it be said that Baldwin's account of the matter is any more successful. In attempting to account for the origin of memory he says, referring to the neural associative machinery: "Such a process thus started gives to consciousness the picture or image of the object which we call a memory."[3] But that is assuming the very fact we are endeavoring to explain. If association were all that is needed to account for the image, how is it that the sensory material which it brings sometimes fuses into the percept and sometimes results in an idea?

Furthermore, the theory that the image should arise, genetically, at the very point where it is needed, is foreign to the evolutionary point of view (save to those who understand teleology). The image, to be sure, has come to be the tool of human purpose. But it was not fashioned in response to purpose. It happened. And we shall shortly have reason to believe that the situation which gives it birth is more closely akin to the day dream than to the typical problematic situation.

How then did its genesis come about? Before attempting a reply to this question, let us first make sure that we understand its meaning. We are *not* attempting to account for the presence of indirectly aroused sensory material in consciousness. Indirect arousal is not the differentia of the image.[4] From the structural point of view, we are trying to account for the presence in consciousness of sensory material which

[1] 'Psychology,' p. 215.

[2] The quotation serves my purposes so well that I could not resist temptation, even though it misrepresents the real views of the author. Professor Angell evidently does not intend the above for a detailed explanation.

[3] 'Mental Development in Child and Race,' p. 286.

[4] See almost any chapter on perception.

does *not* blend into the perceptual situation, but maintains, so to speak, a semi-independent existence of its own, and which constitutes an *object* not only to the 'artificial' introspection of the psychologist, but also the spontaneous attention of the individual. For if we believe that there ever was a conscious organism incapable of forming images, we *must* believe that *all* indirectly aroused sensory material fused with the only other form of consciousness which we know, the perceptual. What we are trying to explain is the freedom of the image.

But the facts of structure will not lead us very far in explaining other facts of structure. The significance of the image is not to be sought in the sensory clothes in which it is garbed, but in the reaction of which it is an integral part. We may hope, therefore, to shed light on our problem by studying the type of reaction peculiar to the image. Let me say at once that I share the view of those who hold that the ideational response is an indirect, nascent motor response leading, typically, to a delayed overt response. The indirect reaction is the means, the delayed reaction the end. If that view be true we may hope to solve our problem by studying the indirect reactions of the growing, developing child. And our problem is that of bringing an indirect reaction to the focus of consciousness.

Suppose now that the six-months-old infant is hungry and that the food object is not 'present to sense.' In the milder initial stages it is conceivable that the tendency will discharge into more or less overt feeding movements. With or without the aid of centrally aroused sensations that form of behavior may serve to satisfy the hunger for the time being. The satisfaction, however, will be transient, and that mode of behavior is incapable of developing into an efficient method of control. The nascent movement is, in the first instance, a direct action. It is not likely to develop into indirect behavior. Very soon the infant will express its dissatisfaction with the present status of the universe by means of entirely overt vocalization, a mode of behavior far more likely to be attended by success, but not a promising beginning for the development of thought.

Again, let us take the development of the direct movement of reaching for an object, which proves to be out of reach, into the indirect pointing gesture. That is, the child learns that reaching for an object in the presence of others is a means of having its desire satisfied. Such a response is indirect, objectively, from the physical, and direct from the social point of view. That is, the gesture does not directly effect a change in the physical object, the doll, to which it is directed, nor does the child intend that it should. It does affect directly the individual to whom it is addressed. Does this type of indirect response lend itself to the production of free imagery? I think not. I need not argue, I think, that in the presence of the perceptual object any relevant sensory material which association may bring will fuse into the percept. On the other hand, I see no reason why nascent gestures of this character should not occur in the absence of the object and constitute an integral part of the psychophysical need of that object. Those whose ideal of perfection is the logical circle may argue that the child *cannot* react to an absent object until after he has the power of creating imagery to represent that object. But whatever may follow from the logic of definition, it is a fact that much of the efficient thinking of people constituted as I am takes place in just that way. The gesture *means* the object. It does not re-present it.

Now, confining ourselves for the moment to adult consciousness, is not the nascent pointing gesture then the free image which we seek? It is capable of becoming an independent object to trained introspection. To be sure, it is not discriminated as a movement or as an image in the direct (non-introspective) situation in which it occurs. But then that is true of most of the sensory stuff usually classed as imagery. At best the degree to which such stuff is attended to, apart from its meaning, depends very largely on the training of the individual and on the temporary direction of attention. Again, I might object to classing the nascent gesture as an image on the ground that we have here kinæsthetic *sensation* rather than imagery. But such a distinction would depend upon an unproven theory. It is by no means

certain that imagery of all kinds is not due to the indirect arousal of the sense-organ. It is a matter of purely verbal definition whether we call a nascent movement an image, and it is not for reasons such as these that I am interested in the *free* image. So, as a matter of definition, and in order to make my point, I shall define the free image as the 'copy' image which not only means the object but which also resembles it.

Now it is obvious that the nascent pointing gesture does not resemble the object which it means and indicates. It may be urged, however, that it is associated with other, *e. g.*, visual imagery which can and does resemble the object. In adult consciousness such is the case with individuals of the visual type. I must admit this for the case of the adult, but I would contend that it is exceedingly improbable that the first copy image of the child arises in this way. For the nascent gesture, as such, is not at the focus of attention. Therefore imagery associated with it would not find a substantive nucleus upon which to crystallize into an ideal object. It is not the shape or color of the doll which the child desires. It wants to play. Accordingly visual imagery, if it comes at all, will find its place in the dim fringe of consciousness and will fuse into the perceptual situation of the moment.

Let us now consider another type of indirect reaction, speech. Overt speech, which most of us believe to be gestural in its genesis, is like all gesture indirect physically and direct socially. The fact that it carries meaning is quite analogous to the fact that the pointing gesture carries meaning. It differs, for our purposes, from other gestures in that it is an activity which, as a matter of fact, is carried on for its own sake. The child, an hour at a time, will prattle away contentedly, and it is safe to assume that his attention is on the activity. If now this activity is inhibited, say by direct command of authority, the conditions are just ripe, I think, for the genesis of free imagery. For the activity, being pleasurable, will tend to be continued for its own sake, will tend to express itself nascently, and will tend to reinstate the sensory material with which it has been associated, in this

case auditory. The association of this auditory imagery with the gesture is more compelling, more compact, than the sensory material brought by the pointing gesture on account of the practical immediacy of the association. That is, it is separated from the gesture with which it is associated by the briefest interval of time. Furthermore, and this is of greater importance, it serves to continue the ongoing pleasurable activity of the moment. It is successful. It is efficient. It *re*-presents the object because it almost reproduces it.

It will occupy the focus of attention because it is almost a replica not only of the object, but also of the activity which *tends* to occupy it. Indeed it really is a matter of indifference whether auditory imagery accompanies the nascent gesture provided it means to the child what the overt gesture meant. Auditory imagery may help toward this end, but it does not seem to be necessary. The problem of the genesis of the free image is really that of getting an act which is indirect *physically and socially* to the focus of consciousness. My entire point is that it is not likely to get there on account of its future usefulness as a means, but is exceedingly likely to do so if it is worth while for its own sake in the present. The free image at the moment of its genesis is a direct, though nascent act. It becomes indirect later as it becomes a means and is built into our hierarchy of habits.

From the time that the image has gained its freedom and is able to occupy the focus of consciousness as an object, its development scarcely needs sketching. Given a substantive nucleus, associated imagery will fuse into it and will enrich the direct awareness of the meaning and the sensory qualities of our ideas. It may come to pass that visual imagery associated with the nascent vocal gesture, probably along with eye movements, will come to displace it entirely. And, to the extent that our ideas become habitual means rather than ends, their richness will fade and vanish and become schematic.

It is, I think, significant to note that from the very moment of its birth the image bears the stamp of individuality and freedom. Not only does it enable the child to continue a satisfying activity, but it frees it to some extent from the

irksome bonds of external authority. The child who has learned the use and control of imagery has reached the point, for the first time in his life, where he can call his soul his own. For the nascent vocal gesture is indirect physically and *socially*.

Summary

Summing up, our argument is as follows: On the structural side, the peculiarity of the image is that it occupies—or can occupy—the focus of consciousness as an object which, somehow, belongs to a realm distinct from the perceptual. On the functional side we find that the image is the sensory aspect of a nascent activity which, as purposive activity, is indirect with reference to this perceptual realm. In the formation of habits we see that such indirect reactions are not attended to after the habit is well formed. But our habits of thought are never quite so automatic that this can take place. Accordingly we *might* classify all non-habitual purposive activity as thought. But such a classification neglects the structural differentia, the non-perceptual texture, of the idea. The suggestion of the present article is that this structural difference is correlated with the fact that thought is indirect socially, and is a development of the direct social gesture. This suggestion gains additional weight (to my mind) from the fact that, without slighting the old distinction between the objective and the subjective, it brings it nearer to common sense. The 'objective' is open to the observation of all; the subjective is experienced by the individual alone. The genesis of thought sketches the coming to consciousness of this distinction. Accordingly it will come to consciousness at a time when privacy of conscious activity *in the presence of others* is of value to the individual.

In conclusion I wish to say that it is not the contention of this paper that the mode of genesis so briefly suggested is the only one possible. I have not aimed to lay down 'the necessary conditions' for the birth of imagery. I do hope that the suggestion will be found plausible and intelligible.

After the above had been written[1] the attention of the

[1] The summary was added later.

writer was called to Miss Washburn's treatment of the 'conditions favoring the development of memory ideas.'[1] Although the similarity of Professor Washburn's account to mine is slight, it may be advisable to discuss it briefly. Professor Washburn does not confine herself to copy images as I do, but deals with ideas in general. Nevertheless she feels that attention to the movement is a necessary condition of its becoming an idea. "Thirdly, one of the conditions of the anticipation of a movement appears to be attention to it when it is originally performed. In order to remember a movement, we must have paid attention to the sensations which its performance occasions."[2] Now whatever may be true of the memory of movements as such, Miss Washburn's statement does not appear to hold of the movements which play an important part in effective thinking. So far as I can see, the eye movements which serve such a function in my own thinking need never have been at the focus of attention until my introspection discovers them. Thus if a certain book is usually to the right of my desk, my attention in actually looking for it will be on the book and on other external objects. The reaction, however, may recur in other surroundings and will *mean* the book. Are such nascent movements ideas? It was for the purpose of avoiding the fruitless discussion of this issue that I confined myself to the copy image. Again, Miss Washburn seems to think that she has solved her problem if she shows that attention has been on the movement when it was originally performed. But it is necessary also to show that attention will be on the movement—I should prefer to say 'on the activity'—as it develops into an idea. That this condition is fulfilled in the case of nascent speech is too obvious for elaboration. Miss Washburn does not mention any specific movements, though her account suggests the wiggling of the toes, the sucking of the thumb, and other infantile behavior.[3] It is far from obvious how movements such as these can develop into effective mental tools.

[1] 'Animal Mind,' second ed., pp. 302–307.
[2] *Op. cit.*, p. 305.
[3] *Op. cit.*, p. 306.

THE HETEROCHROMATIC DIFFERENTIAL THRESHOLD FOR BRIGHTNESS: I. EXPERIMENTAL.[1]

BY LEONARD THOMPSON TROLAND

Harvard University

I. The Problem.

The purpose of the experiments and measurements to be described in this article was primarily to obtain a quantitative estimate of the influence of hue difference upon the threshold for discrimination between differing brightness values. This problem is of interest from a number of points of view. In the first place, it is immediately relevant to the question of the uncertainty of 'equality of brightness' judgments in heterochromatic photometry by 'direct comparison.' Secondly, it has an important bearing upon the problem of the utility and significance of the 'just noticeable difference' as a unit for the measurement of luminosity, and other subjective sensory quantities. Thirdly, the solution of the problem might be expected to throw some light upon the relations of the compared hues themselves.

Fundamental Terms and Definitions.—There are a number of separate factors in the problem which should be clearly distinguished at the outset. In all psycho-physical work, we are forced to deal with two fundamental, parallel quantities or dimensions, those of the *sensation* and of the *stimulus*, respectively. In the present paper, we shall employ the term *luminosity* to stand for the intensity factor of the *sensation;* it will be used as a synonym of 'apparent brightness.' Strictly speaking, the intensity term of the *stimulus* is the radiometric analogue of retinal illumination, *i. e.*, watts per unit retinal area.[2] Expressed in terms of objective *light*,

[1] From the Nela Research Laboratory of the General Electric Co., Cleveland, Ohio.

[2] See my paper, 'On the Measurement of Visual Stimulation Intensities,' J. of Exp. Psychol., 1917, 2, 1–34.

this intensity is measured in lumens per square meter, or in meter-candles. However, the retinal illumination is approximately proportional, with a constant pupillary opening, to the *photometric brightness* of the external stimulus surface, and consequently the stimulus intensity can be expressed very conveniently by means of a unit which the writer has called the *photon*,[1] which represents the state of retinal stimulation accompanying a stimulus surface brightness of one candle per square meter and an effective pupil of one square millimeter. This unit may be said to measure the *physiological intensity* of the stimulus. It is an approximate unit of retinal illumination.

There are at least three possible interpretations of the general term, 'differential threshold for brightness,' which it is important to keep separate in our discussion. They are: (1) the *sensory* (or luminosity) threshold, which is equal, by definition, in the Fechnerian scheme of mental measurement, to one luminosity unit or step; (2) the absolute *stimulus* (or light) threshold, which is the arithmetic difference between the two stimulus values which underlie any single luminosity step; and (3) the *relative* stimulus (or light) threshold, which is the ratio of (2) to the higher of the two absolute light values entering into the comparison. (2) is sometimes called the 'sensibility' to differences in light intensity, and (3) the 'Fechner fraction.' Nutting has recently named the reciprocal of this fraction 'the discrimination factor.'[2]

Both the absolute and the relative stimulus thresholds can be considered in reference to (1) the retinal illumination, or (2) the photometric brightness of the external stimulus surfaces. They can be expressed in radiometric as well as in photometric units, and can be derived from measurements made in either of these units. However, with a specified and constant pupillary opening, the proportionality existing between retinal illumination and photometric bright-

[1] *Loc. cit.*, pp. 27–33.

[2] Nutting, P. G., 'Effects of Brightness and Contrast in Vision,' *Transactions of the Illuminating Engineering Society*, 1916, 11, 945.

ness permits us to treat these latter measures as if they were identical, if our object is to study only the *relative* stimulus threshold. For any one wave-length of radiation, the photometric and radiometric values are also proportional, and their ratios for different wave-lengths are given by the visibility curve. In the present discussion our principal concern is with influence of color difference upon the *relative* threshold; absolute intensities will be expressed in photons.

Formulation of the Problem.—The nature of our specific problem may be described somewhat more in detail as follows: Suppose that C and S are two stimulus fields, filled uniformly with light. Let the intensity of the stimulus in C be h and in S be i, and let us represent the *color* of C by λ_1, and of S by λ_2, without assuming that λ_1 and λ_2 stand for single wave-lengths.

If Δi is the absolute stimulus threshold, and $i - h = \Delta i$, the relative stimulus threshold must be

$$t = \frac{i - h}{i} = \frac{\Delta i}{i}, \tag{1}$$

assuming $i > h$.

It is a well-established fact that the value of t, although remarkably constant, is nevertheless to some extent a function of practically all of the variables involved in the visual process. Its dependence upon absolute intensity and upon wave-length has been studied very thoroughly by König,[1] and more recently by Nutting.[2] The value of the fraction is influenced, also, by the size of the comparison fields, and by the steepness of the brightness gradient at their junction, if they adjoin, or by their degree of separation, if they are not in juxtaposition. The small differences which exist between the values of the threshold for lights of various wave-lengths, when both of the comparison fields are of the same color, indicate that *color difference* between the two fields must be treated as a factor more or less independent of absolute

[1] König, A., and Brodhun, E., 'Experimentelle Untersuchungen über die psychophysische Fundamentalformel in Bezug auf den Gesichtssinn,' *König's Gesammelte Abhandlungen zur Physiologischen Optik*, 1903, 116–140.

[2] *Loc. cit.*, 944–946.

color, since in heterochromatic photometry by direct comparison a very marked increase in the threshold is encountered.

If the color difference between the fields, C and S, be represented by $\lambda_2 - \lambda_1$, our problem may be stated as that of determining the general form of the function, $f(\ )$, in

$$(a) \qquad t = f(\lambda_2 - \lambda_1).$$

Color and color difference can be expressed in terms of position on a subjective hue scale, as well as in terms of wavelength, so that it will be possible to rewrite (a) in psychological units, a transformation which may prove of theoretical, if not of practical interest.

II. The Literature of the Subject

So far as the writer has been able to determine, no systematic studies have previously been made upon the problem formulated above. The very small amount of data in the literature, which bear upon it, consist in the mean variations of measurements in heterochromatic photometry, usually involving a comparison between a 'white' standard and a color. However, in many of the researches relating to heterochromatic photometry, quantitative estimates of the precision of the measurements appear not to have been made. The mean variations of König's classical visibility measurements are given as of the order of magnitude of 5 per cent.[1] Most of the later work on visibility, having been done by the method of flicker, throws little light upon our problem. Helmoltz[2] found that with his color-mixing apparatus, the mean variation of 25 observations, was 3.0 per cent. for the comparison of red with red, 3.3 per cent for the comparison of blue with blue, and 5.8 per cent. for the comparison of red with blue.

Ferree and Rand[3] state the mean variation of photo-

[1] König, A., 'Ueber den Helligkeitswerth der Spectralfarben bei verschiedener absoluter Intensität,' *König's Gesammelte Abhandlungen zur Physiologischen Optik*, 1903, p. 184.

[2] Helmholtz, H. von, 'Handbuch der physiologischen Optik,' IIte Auflage, 1896, p. 430.

[3] Ferree, C. E., and Rand, G., 'A New Method of Heterochromatic Photometry,' J. of Exp. Psychol., 1916, 1, p. 9.

metric equations between a (tungsten) 'white' standard and a red of 768–650 $\mu\mu$ to be 2.5 per cent. and 'the smallest amount of change which can be detected' is 4.8 per cent. on the average; for a blue-green of 465–520 $\mu\mu$ (compared with the white) the corresponding values are 4.5 per cent. and 8.0 per cent. In other work,[1] using a 0.9 degree field, the same workers found the least perceptible change in the brightness of the white in comparison with the above specified red to be 6.6 per cent. for one observer, and 7.0 per cent. for another; with the green, 6.6 per cent. for the first observer and 8.4 per cent. for the second.

Recently, very exhaustive tests have been made by Crittenden and Richtmyer[2] on the precision of photometric comparisons of lights showing relatively small color differences, representative of various modern types of illuminants. The mean of the residuals for such comparisons between the light of a 4 w. p. c. carbon lamps and a vacuum tungsten at about 1.2 w. p. c.—or equivalent combinations of colored glass filters—was found to be 1.9 per cent. for 114 observers. The observers could be divided into three classes, 31 showing a mean variation of 1.2 per cent; 58, one of 1.5 per cent; and 25, one of 3.5 per cent. with a 2-degree field.

The most interesting data available seem to be those presented graphically by Ives, in his well-known monograph on the flicker photometer,[3] from which the figures in Table I. are drawn. They represent the average of the 'mean errors' (m.v.) made by five observers in the equation by direct comparison, of spectral lights of the given wave-length with the light from a 4.85 w.p.m.s.c. carbon lamp, reflected from a magnesium oxide surface. The field size was 4.58 degrees (diameter), and the two intensities employed were equivalent

[1] Ferree, C. E., and Rand, G., 'A Preliminary Study of the Deficiencies of the Method of Flicker for the Photometry of Lights of Different Colors,' PSYCHOL. REV., 1915, 22, 139.

[2] Crittenden, E. C., and Richtmyer, F. K., 'An "Average Eye" for Heterochromatic Photometry, and a Comparison of a Flicker and an Equality-of-Brightness Photometer,' *Transactions of the Illuminating Engineering Society*, 1916, 11, 331–356, esp. 344.

[3] Ives, H. E., 'Studies in the Photometry of Lights of Different Colors,' I., *Phil. Mag.*, 1912 (6), 24, Plate III., Figs. 2 and 3.

to 76.0 and 30.4 photons, respectively. An examination of the table shows that there is a tendency for the value of the variation to be larger at the ends of the spectrum than in the middle, a fact which may be attributed either to the

TABLE I

PERCENTAGE MEAN VARIATIONS OF PHOTOMETRIC EQUATIONS BY DIRECT COMPARISON BETWEEN A 4.85 W.P.C. CARBON LAMP STANDARD WHITE AND SPECTRAL COLORS (FROM IVES)

Wave-Length	M. V. at Intensity of 76.0 Photons	M. V. at Intensity of 30.4 Photons
653	8.3	5.6
643	6.9	5.3
632	6.3	4.3
622	6.5	3.3
612	4.5	3.9
594	3.7	3.1
574	5.2	2.2
555	4.7	4.1
545	7.9	4.9
535	3.1	3.6
526	4.7	6.0
517	7.0	6.7
Averages	5.74	4.43

relatively low inherent saturation of the mid spectral colors, or to their closer approximation in hue to the unsaturated color of the standard, or to both causes. The average mean variation, for all colors, at 76.0 photons is 5.74 per cent. and at 30.4 photons is 4.43 per cent.

III. APPARATUS AND EXPERIMENTAL METHOD

Description of Apparatus.—The arrangement of the apparatus which was used in the present work is shown schematically in Fig. 1. The principal element is a Lummer-Brodhun spectrophotometer, which has been provided with an additional collimator system, C_3. The light from this system is reflected by an adjustable and removable mirror, M_2, so that it exactly replaces the light naturally proceeding from C_2. B is a regular Lummer-Brodhun cube, with the usual contrast pattern, but the contrast strips have been removed. The rotation of M_2 about a vertical axis by means

of a micrometer screw determines the portion of the spectrum which passes through the telescope slit, S_4. The light from a straight filament lamp, L_4, can be thrown upon M_2 by means of the lens, N_4, in such a way that an image of the filament is formed on the scale, Sc; this permits the calibration of the positions of the mirror with respect to the wave-length passing through S_4, from C_3.

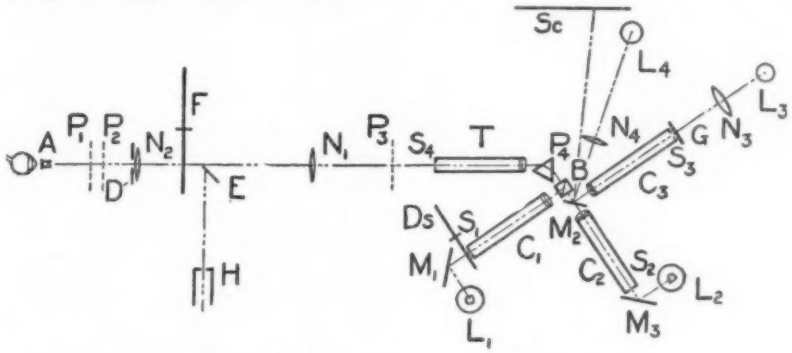


FIG. 1. Schematic plan of apparatus. (See text for explanation.)

The light from the collimator, C_1, is reflected in the prism, B, in the usual manner, from the remaining portion of the photometric field pattern. C_2 is used only for *homochromatic* comparisons, by removal of the mirror. The slits, S_1 and S_2, are illuminated by the light from 100-watt, 110-volt Mazda C lamps, reflected from thin plate-glass mirrors, M_1 and M_2, respectively, the surfaces of which have been ground with 60′ carborundum. In front of S_1 is a Hyde variable sectored disk,[1] Ds, which is rotated at a high speed by an electric motor. The slit, S_3, is illuminated by the image of the small coiled filament of the Mazda C automobile headlight lamp, L_3, which is condensed by the lens, N_3, upon the finely ground diffusing glass, G. The candle-power of L_3 can be varied, with insensible gradations, by means of a rheostat. L_1 and L_2 are operated on a 110-volt generator circuit of constant voltage, and L_3 on storage cells.

The light from the slit, S_4, is caught by the 3.5 diopter

[1] See Hyde, E. P., 'Slit-width Corrections in Spectrophotometry and a New Form of Variable Sectored Disk,' *Astrophysical Journal*, 1912, **35**, 257–267.

lens, N_1, and converged sufficiently so that the cone is completely intercepted by a second lens, N_2—of 3.25 diopters—which converges the light again, upon the artificial pupil, *A*. Just in front of N_2 is a diaphragm, *D*, which limits the size of the illuminated field, seen by the subject. *F* is a flicker photometer disk, used in measuring the stimulus brightnesses, and *E* is a white reflecting surface which can be brought into one half of the field, when desired, and illuminated by the spectral light from a Hilger monochromatic illuminator, *H*.

Calibration of M_2 and C_3 was accomplished by means of color-matches, with the aid of the last-mentioned arrangement. This method—because of the necessity of repeated recalibration—was the only practicable one, and for the most important regions of the spectrum is as sensitive as the direct physical method (using a helium tube) which was employed in the calibration of C_1. C_2 was set by color match in the yellow, so as to give the same range of the spectrum as did C_1 for all positions of the telescope, *T*. The scale on the wave-length drum of the Hilger instrument was carefully tested with the sodium line, and found to be correct.

At P_1, P_2 and P_3, small totally reflecting prisms—not shown in the drawing—were employed to change the path of the light. The first two prisms formed part of the writer's artificial pupil apparatus, with its arrangement for shifting the stimulus from one eye to the other without altering the optical point of view; and the third was necessitated by limitations of space in the disposal of the instruments. Care was taken to keep all of the glass surfaces well polished, and tests showed that the amount of scattered light which they introduced was so small as to be negligible, except in certain cases where special precautions were taken to eliminate it.

A solid and comfortable head-rest was employed, in front of *A*, and a square artificial pupil, 2.51 mm. on a side, was used. When the observer placed his eye before this he saw a clearly defined image of the pattern of the Lummer-Brodhun cube, *B*, projected on the lens, N_2, but delimited by the diaphragm, *D*. All of the measurements were made with the right eye,

and approximate registration of the natural pupil with respect to the artificial pupil was secured through adjustments of the head—by trial and error—so as to give a maximum and constant apparent brightness to the field.

Owing to the different angles of refraction of the lights used in the two portions of the Lummer-Brodhun field, there was a marked overlapping— to the right or left—of the colors, when these were at all widely separated in the spectrum. To eliminate this disturbing effect, the diaphragm, *D*, was cut in such a way as to exclude the parts of the field in which this overlapping occurred. The resulting field pattern is drawn, to scale, in Fig. 2, the over-all dimensions being 2.62

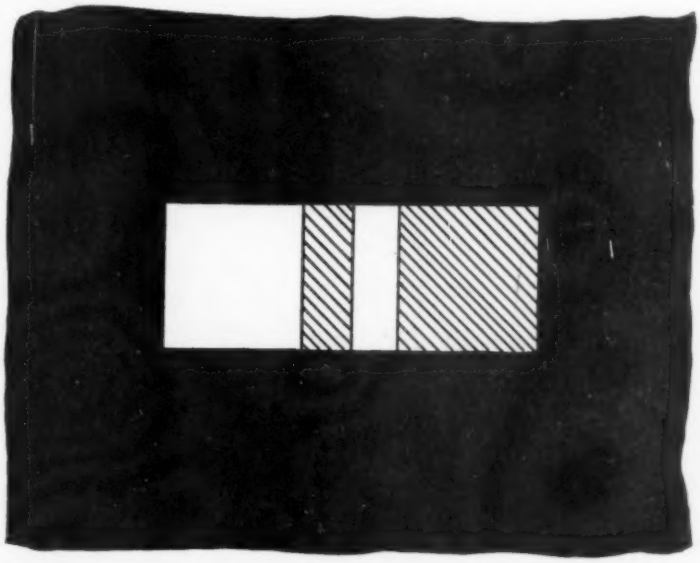


FIG. 2. The pattern of the photometric field. The shaded portion was occupied by the 'standard' color, *S*, the unshaded portion by the 'comparison' color, *C*.

by 1.02 degrees, and the width of each of the middle bands, 0.34 degrees. The general pattern remained unchanged throughout the experiment. The shaded portion (in Fig. 2) was occupied by the standard color (*S*), derived from C_1, and the unshaded part by the comparison color (*C*), derived from either C_3 (heterochromatic comparison) or C_2 (homo-

chromatic comparison). The field was viewed against a completely dark background, and while a judgment was being made, attention was directed to the central line of demarcation, so that the image of the field must have fallen entirely upon the rod-free region of the retina, which is estimated as about three degrees in diameter.[1]

The general conditions of observation were made, as closely as could be, the same as those surrounding general photometric work. The observer's eyes were protected from all direct, glaring light, but the room was diffusely illuminated by the lamps forming part of the apparatus. This diffuse light, however, was quite cut off from the visual field during an observation. Since stimulation was confined to the cones, in the experiment, the degree of scotopic adaptation of the subject's eye was a matter of secondary or of no importance.

Experimental Procedure.—Four colors, corresponding in spectral position with the so-called psychological primaries, red, yellow, green, and blue, were chosen as standards. The mean wave-lengths of the spectral ranges employed were 693, 575, 505, and 475 $\mu\mu$, respectively. These standards were compared with each other, and with nine additional colors taken at intervals of 30 $\mu\mu$ across the spectrum, starting with 430 $\mu\mu$, which was the farthest violet which could be obtained in sufficient intensity. To reduce the proportion of scattered white light, introduced by the natural defects of the spectrometer system, color filters of appropriate selective transmission were employed before the collimator slits for lights lying at the extremes of the spectrum.

The magnitudes of the wave-length ranges of the standards and comparison colors, as calculated from the slit-widths, and other dimensions of the optical systems, are given in Table II. The ranges of the comparison lights used with the blue standard differ from those for the other three standards, because of the use of a wider telescope slit, S_4, which was necessary in order to obtain a field brightness equal to that of the other standards. The range estimates given in the table are accurate to about 1 $\mu\mu$. The accuracy of control of the

[1] See Parsons, J. H., 'An Introduction to the Study of Color Vision,' 1915, 10.

'total color' of the ranges concerned, as determined by color-matching is greater than this in the regions of the spectrum where hue changes rapidly with respect to wave-length, and less in regions where the hue change is small.

TABLE II

WAVE-LENGTH RANGES, IN $\mu\mu$, OF STANDARD AND COMPARISON COLORS USED IN THE EXPERIMENTS, AS DETERMINED FROM SLIT-WIDTHS AND OTHER DATA

A. Standard Colors

Mean Wave-length	Limiting Wave-lengths	Range
693	678–708	30
575	570–580	10
505	499–511	12
475	469–481	12

B. Comparison Colors

Mean Wave-length	Limiting Wave-lengths		Range	
	Blue Standard	Other Standards	Blue Standard	Other Standards
693	676–711	682–704	35	22
670	654–686	660–680	32	20
640	626–654	631–649	28	18
610	598–622	602–618	24	16
580	569–591	573–587	22	14
575	565–585	568–582	20	14
550	541–559	544–556	18	12
520	513–527	515–525	14	10
505	499–511	500–510	12	10
490	484–496	486–494	12	8
475	470–480	471–479	10	8
460	456–464	457–463	8	6
430	427–433	428–432	6	4

The principal series of measurements was made at a constant intensity of approximately 25 photons. This corresponded with the highest brightness of the red standard obtainable with a 0.5 mm. collimator slit, and a 0.4 mm. telescope (or ocular) slit. The intensities of the remaining three standards were equated to that of the red by regulating the two slit-widths and, in the case of the yellow and green, also by placing an absorption glass before the collimator lens.

These measurements and equations were accomplished by means of a flicker photometer, using a white disk and a vacuum tungsten lamp, calibrated with respect to voltage in

candles per square meter (brightness of the illuminated disk). The statements of intensity here given are corrected for the absorption of the lens, N_2, and the prisms, P_1 and P_2 (which intervene between the flicker disk and the eye), as well as for the fractional interception of light by the disk, Ds, which was effective during the threshold measurements, although this disc was stationary, and out of the path of the light, when the flicker determinations were being made.

The average accuracy of reduplication of the *absolute* intensities between trials was about 9 per cent. Since a variation of even 100 per cent. has only a slight effect upon the magnitude of the thresholds, this accuracy may be considered satisfactory. It was conditioned by the method employed to establish intensities at the beginning of each series of measurements. The standard was first given its proper value by setting the slits and the rotating sector disk at the scale positions which had been determined for 25 photons. The comparison field was then matched in brightness to the standard by direct (heterochromatic) comparison, through the adjustment—by means of a rheostat—of the voltage across the lamp, L_3. The voltage required for the match was noted, and the lamp was burned at this voltage until the comparison color was changed, when the whole process had to be repeated. The accuracy of maintenance of the candle-power of L_3 during a series of measurements was better than ½ per cent. for the majority of cases.

The threshold measurements proper were made by changing the brightness of the standard itself, through alteration of the position of the rotating sector disk. The disk was controlled directly by the observer, through a system of cords and pulleys. Its scale had been carefully calibrated in terms of the fraction of total light transmitted. A telescope and small lamp were provided so that the scale could be read from the observer's position, although in about one half of the cases the readings were actually taken by an assistant.

In determining the threshold the 'method of limits' was employed. The brightness of the standard, S, was first increased until it was decidedly greater than that of the com-

parison field, *C*, and then it was gradually decreased until it was *just not noticeably brighter* than—or just equal to—*C*. It was then decreased further until it appeared *just noticeably darker* than *C*, then increased again until it was *just not noticeably darker*, and finally it was increased further until it was *just noticeably brighter* than *C*, scale readings being taken at each point. This cycle was repeated five times for each series, making twenty determinations in all. On the average, about six such series could be made at a single sitting, without unduly fatiguing the observer, and as a rule the comparison lights were taken in spectral order. All series of observations in which a progressive drop in successive readings occurred, were rejected and repeated owing to a suspicion of voltage changes. Two observers took part in the work, one—the writer (T.)—having had considerable experience in photometric and visual work, and the other—Mr. Robert Lucas (L.)—being entirely without such experience, but a very careful worker. Two complete sets of measurements were made by the writer and one complete set by Mr. Lucas. Both observers possess normal trichromatic vision.

An extra set of measurements, against a green standard only, was made by the writer at an intensity of 240 photons, in order to study the influence upon the threshold values of small changes in intensity.

No general systematic attempt was made to evaluate the 'space errors' involved in the comparison, since the position of the standard in the field could not readily be changed. However, automatic interchange of the standard colors among themselves naturally occurred on account of their duplication in certain of the comparison colors. Owing to the method employed in the calculation, the term 'space error' cannot be given its usual meaning of an increase or decrease in the apparent value of one of the compared stimuli. It must rather be regarded as an influence exerted upon the magnitude of the threshold itself, according as one color or the other occupies a given portion of the test field, and is made the variable quantity.

IV. The Calculation of the Threshold Values

The values of the thresholds were computed from the scale readings by the following method.

First, the individual values of the scale readings for each of the four *points:* (*a*) just noticeably brighter, (*b*) just not noticeably brighter, (*c*) just noticeably darker, and (*d*) just not noticeably darker, were averaged separately for each different set of conditions. Since the function connecting scale readings with 'transmission' or relative brightness, was of approximately logarithmic form,

$$r = k \log b + k', \tag{2}$$

the 'transmissions' looked up in the calibration table of the disk, corresponding with the averages of the scale-readings (r) would be the geometrical means of the individual transmissions corresponding with the individual scale-readings. Although the difference between the geometrical and arithmetical means in this computation is small, the geometrical mean of the brightnesses is theoretically to be preferred.[1] The geometric means of the averages for (*a*) and (*b*), and for (*c*) and (*d*), respectively, were found by the same method.

Let us designate the first of these values—the average of the brightnesses for 'just noticeably brighter' and 'just not noticeably brighter'—by i, and the second—the average of the brightnesses for 'just noticeably darker' and 'just not noticeably darker'—by j. By derivation: $i = \sqrt{ab}$, and $j = \sqrt{cd}$. Then, if the unknown brightness of the constant comparison field, C, is taken as h, we have, from Weber's law:

$$h/j = i/h, \tag{3}$$

since $h - i$ and $j - h$ are both threshold steps. Hence

$$h = \sqrt{ij} \tag{4}$$

and two equivalent expressions for the relative stimulus threshold, or Fechner fraction, may be written, viz.,

[1] This statement rests on the assumption that an (arithmetic) average based upon a response or sensation scale is to be preferred to one based upon a stimulus scale, the relation between the two scales being logarithmic. An arithmetic average on the response scale obviously corresponds with a geometric one on the stimulus scale.

$$(5) \qquad t = \frac{\sqrt{ij} - j}{\sqrt{ij}} = \frac{i - \sqrt{ij}}{i} .$$

These formulæ follow the convention, recommended by Nutting, of employing the higher of two liminally different brightness as the denominator of the Fechner fraction.

The values of t as computed by means of the last term of (5) for each of the fifty-two different conditions of comparison, at an intensity of 25 photons, and for both subjects, are given in Table III. Each value for subject L. represents at least twenty independent observations, and for subject *T.* from forty to one hundred. Additional measurements were made in certain cases to increase the precision of seemingly aberrant values. The computation of $\sqrt{ij}$ was done on the slide-rule rather than in terms of scale readings, because of the appreciable deviation of the calibration curve from logarithmic form over the large range of scale-readings involved between i and j.

Under v in Table III. are given the average mean variations of the individual brightness values of the four 'points,' (*a*), (*b*), (*c*), and (*d*), expressed as fractions of these values. The magnitudes of v, for each of the fifty-two situations, were computed in the following manner.

First, the mean variations of the scale-readings from their mean were found for each of the points. Owing to the approximately logarithmic form of the calibration curve, a variation of one linear unit of scale-reading could be taken to represent a constant fractional variation in 'transmission' or brightness, viz., 7.2 per cent. per millimeter ($1/k$ of equation 2). Hence, by multiplying the mean variations of the scale-readings by this constant, the *fractional mean variation* of the brightnesses could be found. This fraction was first calculated for each of the four points, and then the arithmetic average, v, of the four fractions was determined for each set of conditions.

The results given in Table III. are shown graphically in Figs. 3 to 6, inclusive. In Table IV., the values of t and v are given for the series of measurements made by subject *T* at 240 photons, with a green standard.

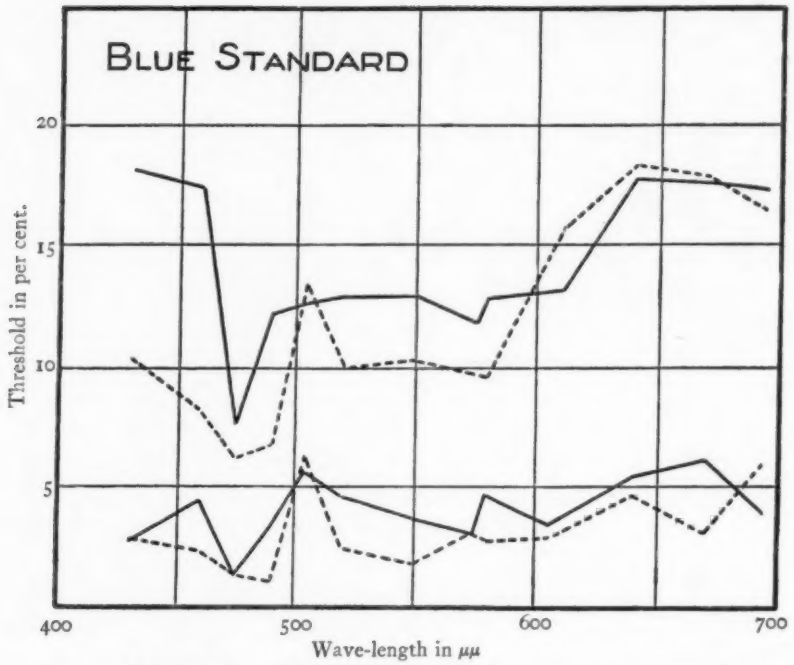


FIG. 3. Threshold and variation values for the blue standard. The values for subject T. are given by the full line, those for subject L. by the broken line.

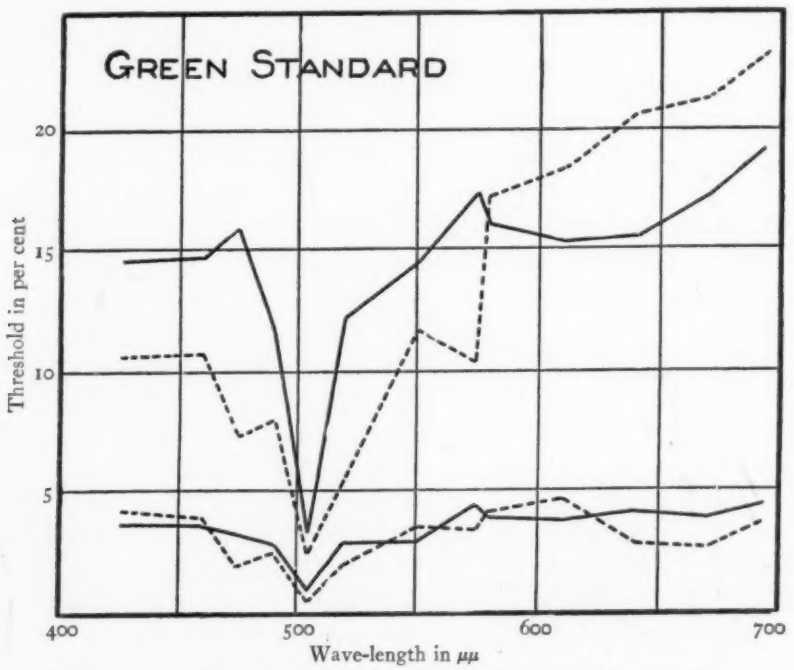


FIG. 4. Threshold and variation values for the green standard. See Fig. 3.

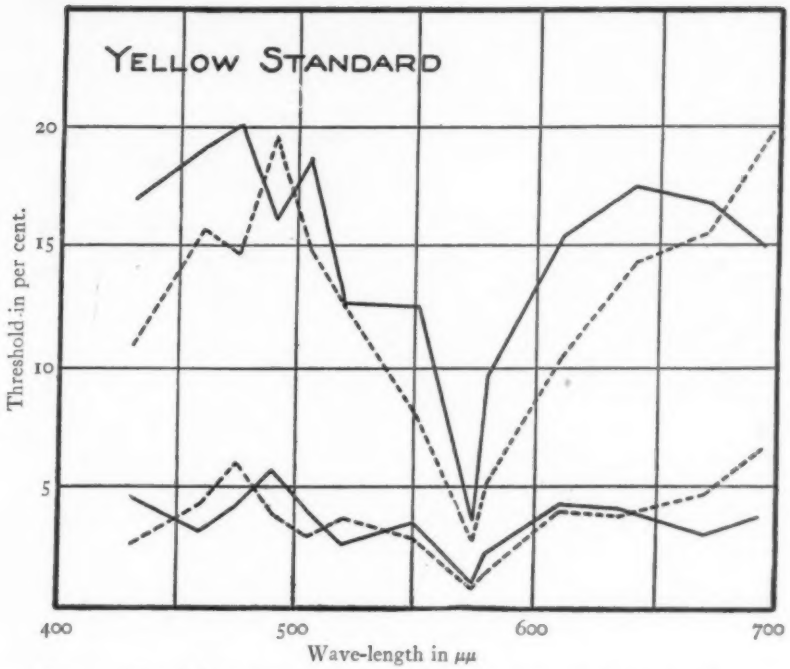


FIG. 5. Threshold and variation values for the yellow standard. See Fig. 3.

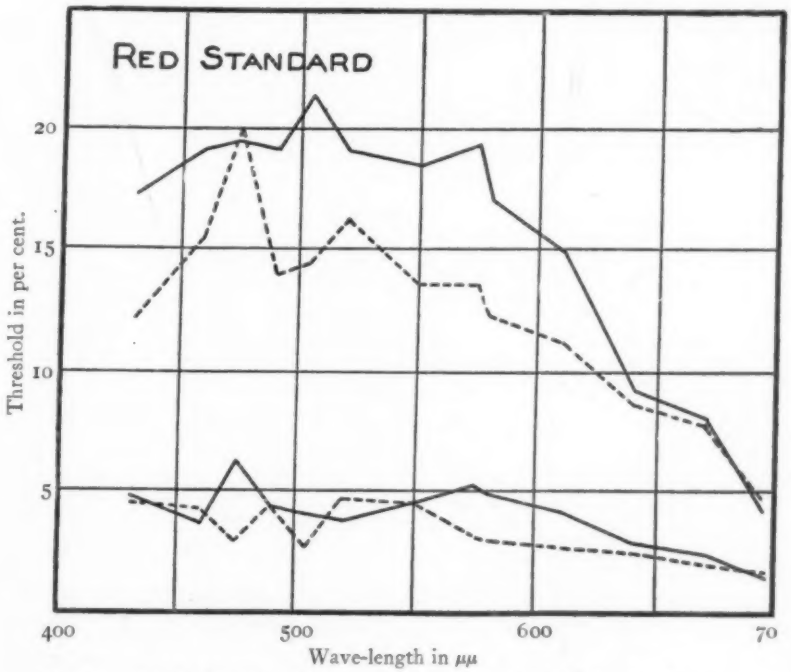


FIG. 6. Threshold and variation values for the red standard. See Fig. 3.

TABLE III

VALUES OF THE HETEROCHROMATIC RELATIVE THRESHOLD, t, FOR BRIGHTNESS DISCRIMINATION, AND THE AVERAGE FRACTIONAL MEAN VARIATION, v, OF THE DETERMINING POINTS OF THE THRESHOLD, FOR TWO SUBJECTS, T. AND L., FOUR STANDARD COLORS, AND THIRTEEN COMPARISON COLORS, AT 25 PHOTONS

Comparison Color, μμ	Standard Color, μμ							
	Blue, 475		Green, 505		Yellow, 575		Red, 693	
	t	v	t	v	t	v	t	v
430, (T.)	.181	.029	.145	.036	.169	.046	.174	.048
(L.)	.104	.027	.107	.042	.109	.026	.122	.045
460, (T.)	.174	.045	.147	.035	.191	.032	.191	.036
(L.)	.081	.023	.149	.038	.156	.043	.154	.042
475, (T.)	.075	.013	.159	.032	.201	.042	.195	.062
(L.)	.062	.013	.072	.019	.147	.060	.199	.028
490, (T.)	.121	.033	.116	.028	.161	.057	.191	.044
(L.)	.067	.010	.079	.024	.196	.039	.139	.044
505, (T.)	.126	.056	.0367	.0095	.185	.041	.214	.040
(L.)	.134	.062	.0237	.0035	.148	.030	.144	.026
520, (T.)	.129	.046	.122	.029	.126	.026	.190	.037
(L.)	.100	.025	.055	.019	.125	.037	.161	.046
505, (T.)	.129	.036	.144	.029	.125	.035	.185	.045
(L.)	.103	.018	.117	.035	.080	.029	.135	.045
575, (T.)	.118	.030	.173	.044	.0369	.010	.194	.052
(L.)	.141	.030	.103	.033	.0275	.0075	.135	.032
580, (T.)	.128	.046	.160	.039	.097	.023	.170	.049
(L.)	.095	.027	.172	.040	.052	.013	.122	.030
610, (T.)	.131	.034	.153	.038	.155	.043	.149	.041
(L.)	.157	.028	.184	.046	.104	.040	.111	.027
640, (T.)	.178	.053	.155	.041	.175	.041	.092	.028
(L.)	.183	.046	.206	.028	.144	.039	.085	.024
670, (T.)	.176	.060	.172	.039	.169	.031	.080	.024
(L.)	.178	.030	.213	.026	.156	.047	.076	.020
693, (T.)	.173	.039	.192	.044	.150	.038	.042	.014
(L.)	.164	.059	.231	.037	.199	.066	.047	.016

TABLE IV

VALUES OF THE HETEROCHROMATIC RELATIVE THRESHOLD, t, FOR BRIGHTNESS DISCRIMINATION, AND THE AVERAGE FRACTIONAL MEAN VARIATION, v, OF THE DETERMINING POINTS OF THE THRESHOLD, FOR ONE SUBJECT, T., A GREEN STANDARD, 505 μμ, AND TWELVE COMPARISON COLORS, AT 240 PHOTONS

Comparison Color, μμ	t	v
460	.175	.051
475	.108	.022
490	.165	.039
505	.0226	.0092
520	.140	.027
550	.152	.045
575	.082	.038
580	.147	.042
610	.213	.048
640	.183	.040
670	.170	.034
693	.187	.053

V. Discussion of Results: *A.* The Relation between Color Difference and the Relative Stimulus Threshold

In discussing the relations existing between the values tabulated above, we shall consider two general problems: (1) the nature of the dependence of the relative stimulus threshold upon color difference, from the point of view, first, of the threshold itself and, second, of the system of colors, and (2) the correlation existing between the threshold and its variation measure. These problems will be discussed (*a*) in their bearing upon practical photometry and (*b*) in relation to the theory of threshold and of color difference.

Comparison with König's Data.—The four *homochromatic* threshold ratios for subject T. are : *R*, .042; *Y* .0369; *G*, .0367; and *B*, .075. For subject L. the corresponding values are: .047, .0275, .0237, and .062. König, at approximately the same intensity (50 units on his scale) found: *R*, .0376; *Y*, .0320; *G*, .0252; and *B*, .0250, for nearly the same selection of wave-lengths.[1] The average value of the homochromatic threshold for subject T. is .0453; for subject L., .0403; for König, .0300.

The larger value of the homochromatic threshold obtained in the present measurements, as compared with König's results, may be attributed to a difference in any of the various factors which influence the magnitude of the threshold. It is probably not due so much to the personal equation as to the fact that König's test-field was much larger than the one employed by the writer, the over-all dimensions of the former being $6 \times 4\frac{1}{3}$ degrees. König's field, also, was divided into two, instead of into four parts. As shown in the table of König's values given by Nutting, an intensity of 25 photons is in the region of relatively rapid change of the threshold ratio as a function of intensity, and some uncertainty exists as to the exact value of König's stimulation units.

The homochromatic threshold for subject T., with the

[1] See Nutting's recalculation of König's data in 'The Luminous Equivalent of Radiation,' *Scientific Papers of the Bureau of Standards*, No. 103, 1908, 286.

green standard, at 240 photons, was 0.226, which is considerably lower than the average for 25 photons.

König's results, for intensities in the neighborhood of 25 photons, show a decrease in the value of the homochromatic threshold in passing from the red to the blue end of the spectrum, whereas in our data the threshold in the blue is, for both subjects, approximately twice the average value of the other homochromatic thresholds. The decrease shown in König's results is probably due to the increased ratio of rod response to cone response in the blue as compared with the red, as his field was sufficiently large to stimulate an appreciable number of rods. In the present writer's experiments, however, the stimulation was practically limited to the rod-free region of the retina.

The 'Heterochromatic Comparison Factor' as a Function of Color Difference.—In order to abstract the influence of color difference upon the threshold from that of other variables each threshold value can be divided by the corresponding homochromatic value, *i. e.*, all of the thresholds can be expressed in terms of the homochromatic threshold as a unit. This expression, or ratio, may be called the *heterochromatic comparison factor.* Such a reduction of course assumes that the influences exerted by the other factors are themselves independent of color difference. Although this assumption is probably not completely accurate, it may be regarded as a useful approximation to the truth, since within certain widely separated limits the influence of the other factors is small compared with that of color difference.

The values of the heterochromatic factor as calculated for all of the thresholds determined at 25 photons intensity, are given in Table V.

In considering the relation between the heterochromatic comparison factor and color difference, it is desirable to express the latter not in terms of wave-length intervals, but in terms of the number of 'just noticeable differences in hue' between any two compared colors. In certain regions of the spectrum, principally in the red, a large wave-length difference may correspond to almost no color difference at all. Fortunately,

TABLE V

VALUES OF THE HETEROCHROMATIC COMPARISON FACTOR, *f*, FOR TWO SUBJECTS, T. AND L., FOUR STANDARD COLORS, AND THIRTEEN COMPARISON COLORS, AT 25 PHOTONS

Comparison Color, μμ	Standard Color, μμ			
	Blue, 475	Green, 505	Yellow, 575	Red, 693
430, (T.)	2.42	3.97	4.54	4.20
(L.)	1.68	4.52	3.96	2.58
460, (T.)	2.32	3.99	4.97	4.60
(L.)	1.31	6.28	5.66	3.26
475, (T.)	1.00	4.33	5.45	4.68
(L.)	1.00	3.04	5.36	4.21
490, (T.)	1.62	3.17	4.37	4.58
(L.)	1.08	3.32	7.12	2.94
505, (T.)	1.68	1.00	5.00	5.15
(L.)	2.17	1.00	5.38	3.04
520, (T.)	1.72	3.32	3.43	4.58
(L.)	1.62	2.31	4.55	3.41
550, (T.)	1.72	3.91	3.40	4.44
(L.)	1.67	4.93	2.91	2.85
575, (T.)	1.58	4.71	1.00	4.65
(L.)	2.27	4.54	1.00	2.85
580, (T.)	1.71	4.35	2.64	4.09
(L.)	1.55	7.24	1.91	2.57
610, (T.)	1.75	4.16	4.20	3.58
(L.)	2.54	7.75	3.76	2.33
640, (T.)	2.38	4.23	4.75	2.22
(L.)	2.97	8.69	5.23	1.79
670, (T.)	2.35	4.69	4.57	1.93
(L.)	2.88	9.00	5.67	1.59
693, (T.)	2.31	5.22	4.07	1.00
(L.)	2.66	9.73	7.22	1.00

TABLE VI

POSITIONS OF COLORS, USED IN THE HETEROCHROMATIC COMPARISONS, ON NUTTING'S HUE SCALE, AND INTERVALS, IN TERMS OF UNITS OF THE SCALE, BETWEEN COMPARISON COLORS AND STANDARDS

Mid Wave-Length, μμ	Hue Scale Position	Hue Scale Interval from Standard.			
		475	505	575	693
430	0.02	−0.22	−0.39	−0.66	−0.98
460	.17	.07	.24	.51	.83
475	.24	.00	.17	.44	.76
490	.34	+0.10	.07	.34	.66
505	.41	.17	.00	.27	.59
520	.47	.23	+0.06	.21	.53
550	.56	.32	.15	.12	.44
575	.68	.44	.27	.00	.32
580	.71	.47	.30	+0.03	.29
610	.84	.60	.43	.16	.16
640	.91	.67	.50	.23	.09
670	.98	.74	.57	.30	.02
693	1.00	.76	.59	.32	.00

Nutting and Jones have worked out very carefully a subjective hue scale of the required sort.[1] The approximate positions, upon Nutting's scale, of the thirteen mid wavelengths employed in our experiments are given in Table VI., and the mean heterochromatic factors, for both subjects, are plotted in Fig. 7, as functions of the distance on the hue scale between the standard and the given comparison colors.

An examination of Fig. 7 brings out a number of interesting points.

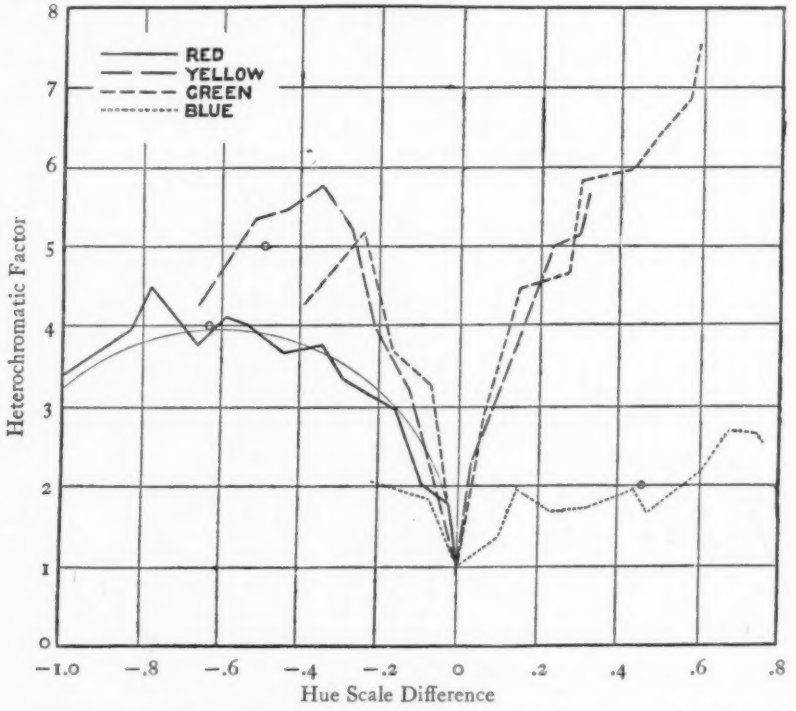


FIG. 7. The heterochromatic comparison factor, as a function of the hue scale interval between the compared colors. The curves represent the average of the results for both subjects.

The relatively small values of the heterochromatic factors obtained with the blue standard are referable, for both subjects, to low values of the heterochromatic thresholds, but

[1] Nutting, P. G., 'The Retinal Sensibilities Related to Illuminating Engineering,' *Transactions of the Illuminating Engineering Society*, 1916, 11, 15.

also and primarily to the very high values of the homochromatic threshold. The cause of this difference between the blue and the other curves is obscure, and the discrepancy is so great that the former set of values must be suspected of being affected by factors which are irrelevant to our present discussion. The difference can scarcely be attributed to an experimental error, depending upon the greater variation in the candle-power of the light sources in the blue, as compared with the red (according to the temperature radiation law), since this would increase the heterochromatic as well as the homochromatic thresholds. The most probable explanation is that, possibly owing to the high refrangibility of the blue light, the subject's eye was unable to form a sharp image of the field upon the retina, so that the brightness gradient between the spatial components of the field was markedly decreased in the blue. This effect would be at a maximum in the comparison of blue with itself, or with violet. It is possible that bad definition at the boundary of the compared fields also decreases the influence of color difference upon the threshold—by diminishing color contrast—so that one and the same factor could operate to increase the homochromatic and to decrease the heterochromatic threshold.

It is of course evident from the qualitative data previously at hand that the heterochromatic factor must exhibit a minimum for a minimum of color difference between the standard and the comparison fields. However, except for this generalization, the form of the function connecting the threshold with degree of color difference has remained undetermined. Although considerable deviations from regularity are shown by the points of Fig. 7, they nevertheless fall upon what, for psycho-physical threshold data, may be regarded as fairly smooth curves. It will be seen that, in general, the threshold tends to increase in passing from the standard to the neighborhood of its *complementary*, beyond which it begins once more to decrease. However, the increase is larger for a given increment of color difference, when this is added to a previously given small difference, than when it is added to a difference which is already large. This is

especially apparent in the case of the curve for the red standard.

Unfortunately, Nutting's hue scale, as published, does not include the purples; if it did, the scale would obviously become cyclical. It is evident, also, that if the heterochromatic threshold measurements were extended over the whole cycle of hues, each of the curves of Fig. 7 would necessarily intersect the ordinate, unity, at two points, although these points would both represent the same hue.

The curve for the data obtained with the red standard is the most regular and continuous of the four, and may be selected for special study. The best representative smooth curve for these data, as plotted, does not differ a great deal from an arc of a circle having its center on the ordinate, unity at a point corresponding in the hue scale with a wavelength of about 500 $\mu\mu$. The equation for this circle, when expressed in terms of the plotted variables, is that of an ellipse:

$$\frac{(.61 - h)^2}{.61^2} + \frac{(1 - f)^2}{2.96^2} = 1, \tag{6}$$

where h is the relative position on the hue scale, and f is the value of the heterochromatic factor. This equation simplifies to

$$f = 1 + 2.96\sqrt{3.28\,h - 2.69\,h^2}. \tag{7}$$

For a value of $h = 1.22$, the curve again cuts the axis of the abscissæ, and for values larger than this f is an imaginary quantity.

Too much emphasis can easily be laid upon the significance of the above mathematics. The data are, of course, relatively crude for purposes of curve-fitting, and it is probable that factors of asymmetry have been introduced into all of the curves, on account of optical effects due to the variation in refrangibility of the stimuli form different parts of the spectrum. However, the general form of the relation between the differential threshold for brightness, and color difference, may be regarded as determined by the above reasoning.

The heterochromatic factor is roughly proportional to the number of just noticeable homochromatic luminosity steps

contained in a given heterochromatic step, if such an expression will be permitted. The exact number, n, of homochromatic steps equivalent to a given heterochromatic step can be found by use of the formula:

$$n = \frac{\log (1 - fm)}{\log (1 - m)}, \tag{8}$$

where f is the heterochromatic factor, and m is the relative (fractional) homochromatic threshold. This formula follows directly from the definitions of the various concepts which are involved. If the data of Fig. 7 were plotted in terms of n instead of f, the values of the ordinates would be slightly greater and the curves would be somewhat more elongate than is actually the case. For example, the n corresponding with the heterochromatic factor 4.00 (520 $\mu\mu$) for the red standard, is 4.38, and for the factor 2.96 (610, same standard), is 3.12. A graph using h and n as coördinates would be expressed entirely in terms of subjective scales of quality.

The feature of the above studies which is perhaps of the greatest practical importance for photometry is the relatively great influence exerted upon the brightness threshold by small color differences, such as are met with, for example, in the comparison of the light emitted by incandescent bodies at different 'color temperatures.' Assuming 134 just noticeable differences of hue in the entire spectrum, calculation based upon equation (7) shows that a threshold difference in hue should raise the heterochromatic factor from unity to 1.45.

RATE OF PUPILLARY DILATION AND CONTRACTION[1]

BY PRENTICE REEVES

In a recent determination of the least amount of radiation capable of giving rise to a perception it was necessary to know the diameter of the pupil when fully adapted to darkness.[2] The results in the literature were few and discordant,[3] so that it was decided to measure the pupils of the observers used in the experiment. In the general investigation which is being carried out in the Eastman Kodak Research Laboratory under the description of "Visual Sensitometry" the sensibility of the retina is examined throughout a range of light intensity from total darkness to a brightness obtained by reflecting full sunlight from white paper. For each brightness used the pupil has a certain diameter and the problem was to determine these values for several subjects. In parts of this study of retinal sensibility it was possible to use only one eye, the other being closed, and this introduced the problem of the effect of exposing one or both eyes to the given

[1] Communication No. 66 from the Research Laboratory of the Eastman Kodak Company. Paper read before the American Psychological Association at Pittsburgh, December, 1917.

[2] Prentice Reeves, 'Minimum Radiation Visually Perceptible.' *Astrophysical J.*, 1917, 46, 167–174.

[3] T. H. Blakesley (*Phil. Mag.*, 1910, *29*, 960–969) reports a maximum diameter of 6.74 to 7.20 mm., Nutting says the pupil ranges from 2 mm. to 8 mm., though he measured only 6.9 mm. for a brightness of log − 5 millilamberts (*Trans. Illum. Eng. Soc.*, 1916, *11*, 1–21). Stevenson found an average maximum of 8.5 mm. with a mean variation of only 3 per cent. (*J. of Brit. Astron. Assn.*, 1916, **26**, 303). With a preliminary method comparable to that of Blakesley and Nutting the writer found an average maximum of 6.8 mm. for his own pupil while flashlight photographs gave a maximum of 8.3. All evidences seem to point to wide variations between observers as well as in the same individual's pupil from time to time, which seems to disagree with Stevenson's results. See Troland, PSYCHOL. REV., 1915, **22**, 167–176. Results by Langfeld show a small diameter (*Zsch. f. Sinnesphysiol.*, 1908, **42**, 349–358).

brightness. This is a study of the so-called consensual reflex.[1] The rate of change of sensibility when going from one brightness to another is still another part of the general research which involves a special consideration of the pupil. The change in sensibility, such as occurs when passing from a brightly lighted room to a darker one or vice versa, results from the operation of two factors, a retinal process (whatever it may be) and the change in the diameter of the pupil. The latter then calls for the determination of the rate of opening and closing of the pupil, that is, a quantitative determination of the pupillary reflex.

In the first part of this work, the investigation of the consensual reflex and the diameter of the fully dark adapted pupil, instantaneous photographs were taken with a 5 x 7 view camera. The subject was focused on the ground glass of the camera, fixed in a head rest, adapted to total darkness for at least fifteen minutes and then the flashlight taken. In the determination of the minimum radiation visually perceptible three observers were used who had pupillary maxima of 8.4, 8.3 and 7.4 mm. giving an average of 8.0 mm. A small millimeter scale was placed in the plane of the pupil so that it would be magnified to the same extent as the pupil and make the records easy to read. For two of these observers several series of photographs were taken over eight brightness levels including total darkness at one end and the reflection of full sunlight from white paper at the other end. The effect of exposing one or both eyes to the sensitizing brightness was studied throughout this entire range of intensities. The shape of the curves plotted for the two subjects is about the same, though the actual pupillary diameters show individual differences. Fig. 1 shows the curves obtained from one observer and we see that over the range of ordinary brightness the closing of one eye markedly increases the diameter of the pupil. Fig. 2 shows some of the photographs and the data plotted in the previous figure. We see from these results that

[1] Dunn (*Arch. of Ophth.*, 1917, 46, 193–210) says "when both eyes are normal, no matter what the difference of illumination before the two eyes, the two pupils remain of practically the same size—this is the result of what is called the consensual light reflex."

the decrease in the diameter of the pupil after the intensity increases beyond 100 millilamberts is slight so that in further experiments the maximum intensity used was in the vicinity of 100 ml. This gives a minimum diameter of the pupil near enough to the actual minimum and yet avoids the exposure of the subject's eyes to a highly unpleasa nt g are.

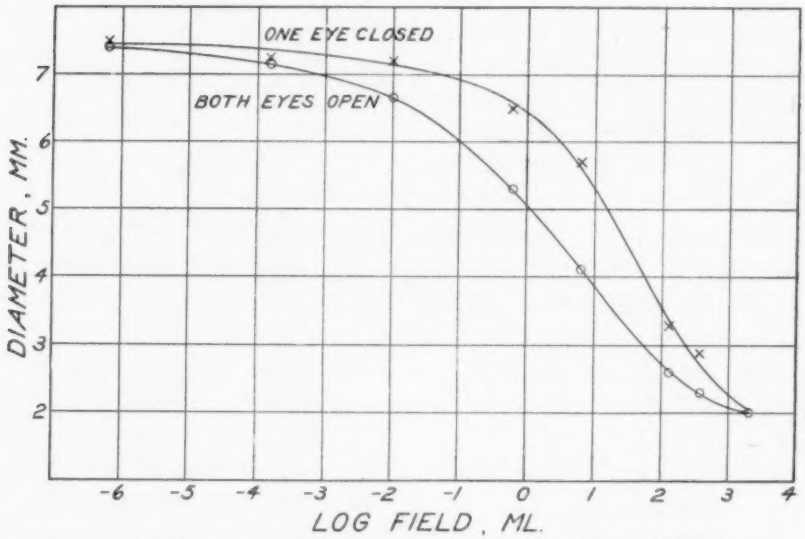


FIG. 1. Effect of Exposing One or Both Eyes on Diameter of the Pupil.

From these results six suitable brightness levels were chosen and the eyes of six other subjects were measured when both eyes were exposed. One of the first subjects was also used in this part of the experiment as a check on the method. A motion-picture camera was used in place of the view camera, and a bank of lamps replaced the flash powder. An extension was used on the lens so that a full-sized image was recorded on the film. After sufficient time for adaptation to the sensitizing brightness electrical connections, operated by the experimenter, started the motor driving the motion-picture camera to introduce unexposed film, the taking lights were turned on and the picture was taken. Several pictures were taken of each subject on different days and the results averaged. Fig. 3 shows the curves for six subjects with the

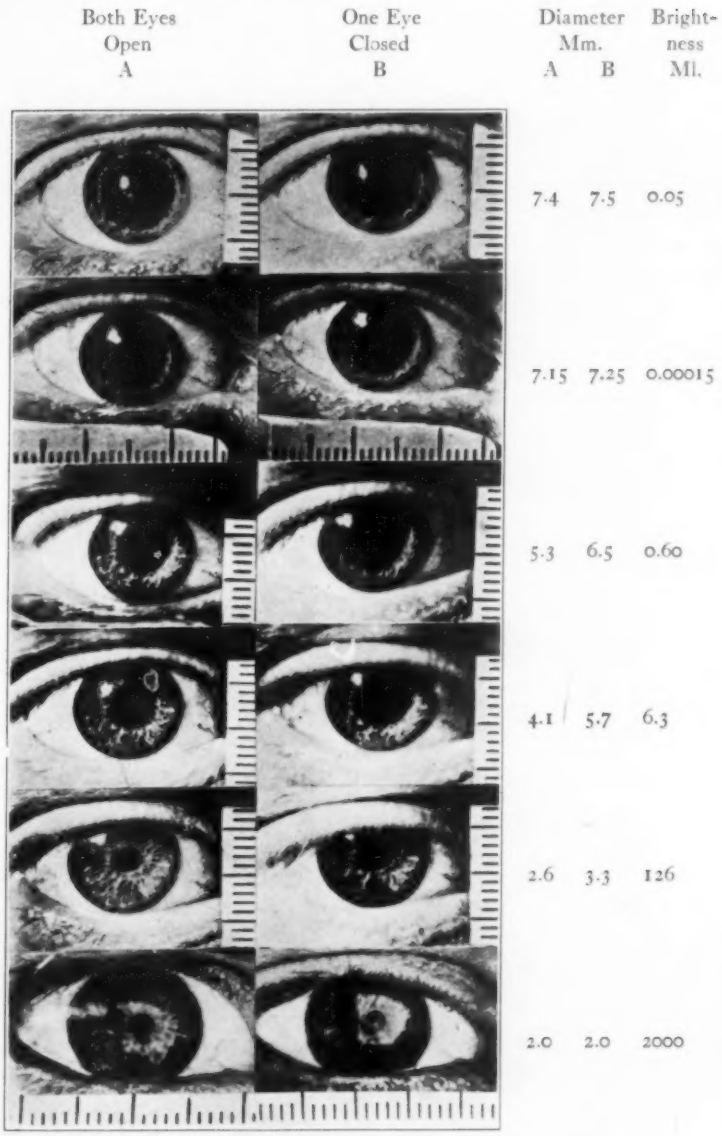


FIG. 2. Effect of Closing One or Both Eyes on Diameter of the Pupil.

average represented by the heavy curve. We notice individual differences in these curves and rather large variations in the maximum diameters of the pupils. Fig. 4 shows some

of the actual photographs taken and the data for the average of all seven subjects.

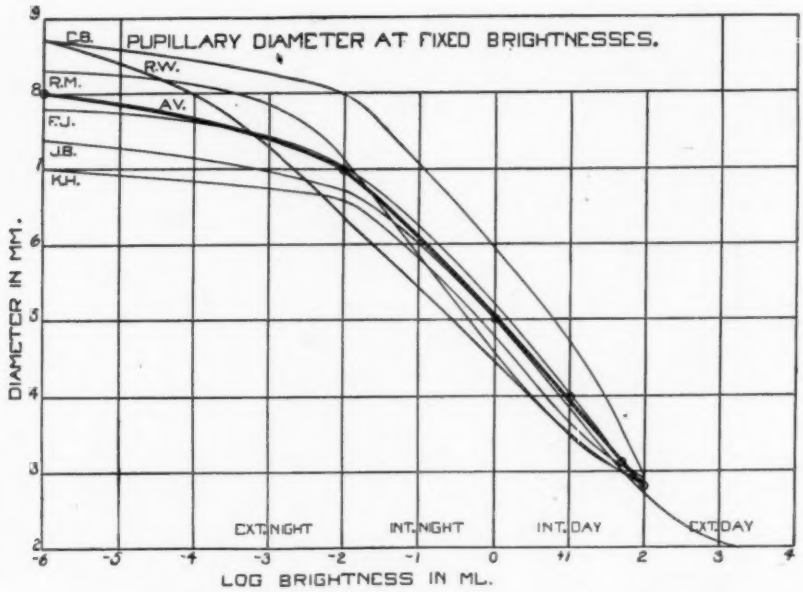


FIG. 3

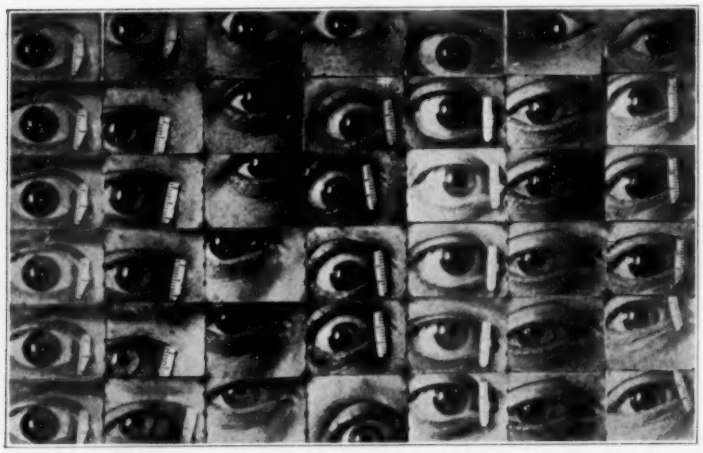


FIG. 4. Pupillary diameter at fixed brightness.

The rate of closing of the pupil was measured by taking motion pictures of an eye fully adapted to total darkness (so as to get the maximum pupil) as it closed to the minimum diameter chosen. By means of the electrical connections of the apparatus the motion-picture camera could be operated at a speed that gave pictures a tenth of a second apart so that, with the pupils readily measurable, it was an easy task to get the rate of closing. The previous six subjects were used as well as two others and Fig. 5 shows the curves from the six.

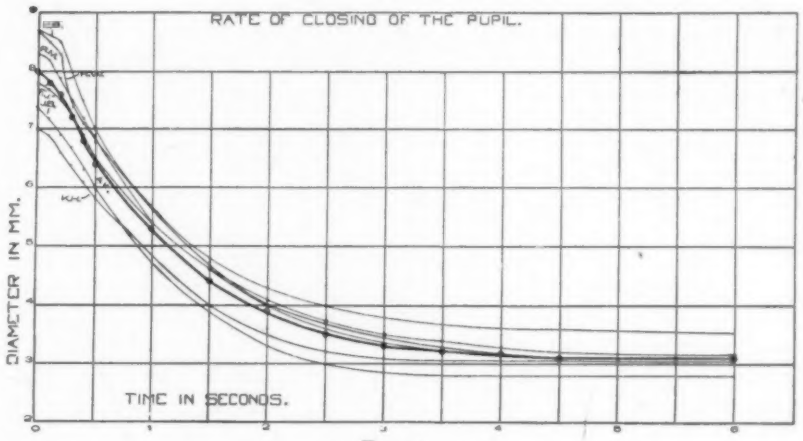


FIG. 5

It can be seen that the average pupil reached its minimum in less than five seconds, the greater part of the closing occurring within the first two seconds. Fig. 6 shows the photographs and average data from the eight subjects. An inspection of these photographs will show the variations between subjects.

In obtaining the rate of opening of the pupil a paradox presented itself, since we must have darkness to get the pupil to open but we must have light to get a photographic record. So an electrical device was made which turned off the lights for any desired time, started the motion-picture camera, again turned on the taking lights and photographically recorded the amount of opening after the given time in darkness. From a preliminary series suitable time intervals were chosen and the time and rate of opening of the pupil was obtained

for seven subjects. Fig. 7 shows the curves of the six subjects, and it is seen that the average pupil required from three to ten minutes to reach its maximum diameter from the initial diameter as chosen. Fig. 8 shows the photographs of

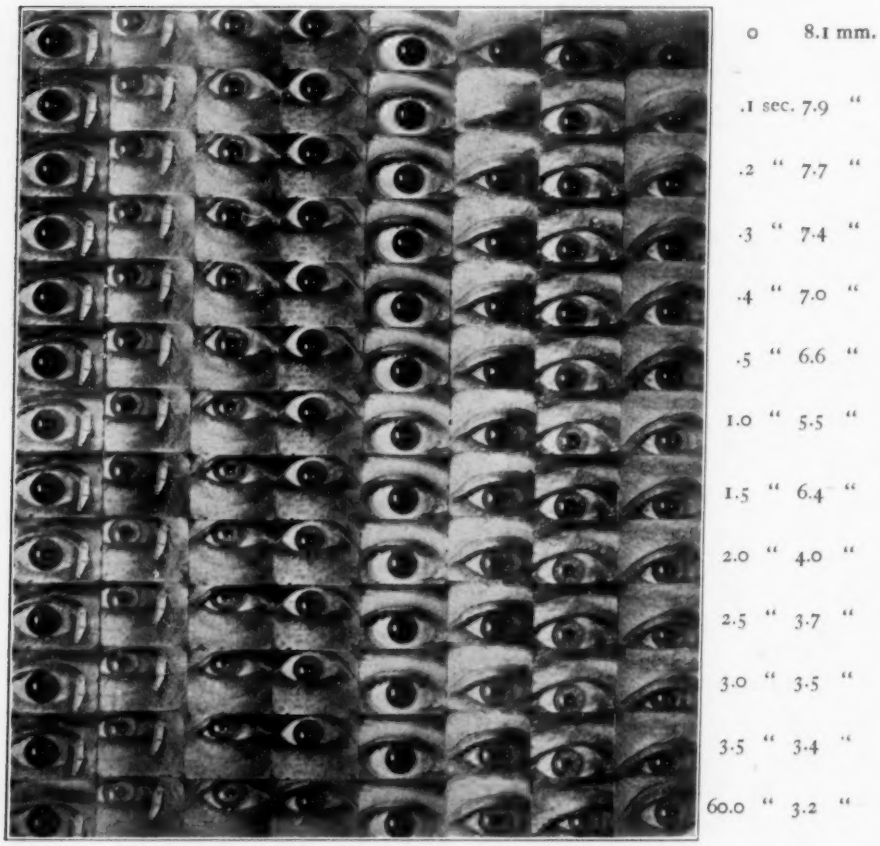


FIG. 6. Rate of closing of the pupil.

several stages in the process of opening. It is interesting to compare the rate of opening with the rate of closing; the time for opening to a maximum averages about five minutes as compared to the same number of seconds for closing.

It is a well-established fact that pupillary diameter varies

with the convergence, so in order to keep this factor constant a fixation point at a distance of 35 cm. was used. In darkness an illuminated pinhole was used, the intensity of which was kept at a just perceptible intensity for a few seconds just before the picture was to be taken by means of a variable rheostat controlled by the subject himself. Each subject

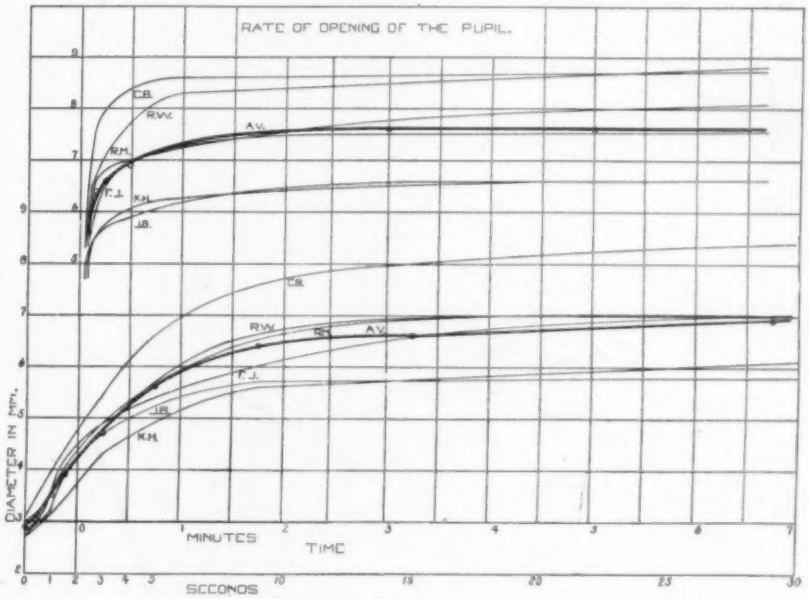


FIG. 7

was photographed at least four times for each of the curves plotted and some of them sat for as high as twenty series. The data plotted are averages of all series, and are shown in the four tables. Previous investigations of the pupil show that the color of the iris has no effect on its action, but that age is a factor.[1] In this study, however, none of the subjects were old enough to show a marked effect of age.

It must be remembered that in the results for the opening and closing of the pupil two definite brightnesses were used and that the time and rate of functioning of the pupillary reflex in changing from one brightness to the other is probably

[1] Kanngieser, F., *Arch. f. Augenhk.*, 1909, **63**, 78–87. Langfeld, *op. cit.*

true for that change only. That is, if any other combination of intensities be used we could expect a different rate for the reflex action. Another thing to bear in mind is that practi-

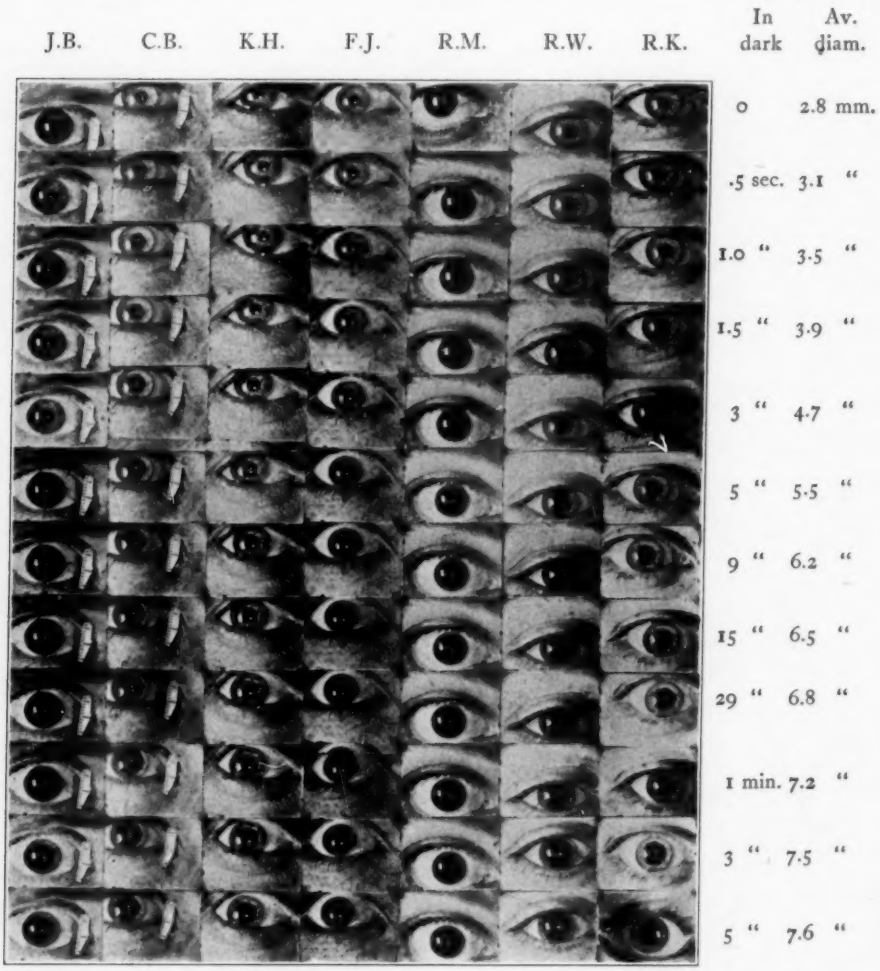


FIG. 8. Rate of opening of the pupil.

cally white light, tungsten filaments and sunlight, was used and that we might expect different results for colored light and especially for monochromatic sources. In working out the time and rate of adaptation curves marked differences

were found for different colored lights and for different intensities of the same light. As the pupillary action is one part of the process of adaptation we can safely make the above

TABLE I

EFFECT OF CLOSING ONE EYE ON PUPILLARY DIAMETERS

Brightness in Millilamberts	Log *B*	Both Eyes Exposed		One Eye Closed		Difference	
		J.B.	P.R.	J.B.	P.R.	J.B.	P.R.
0.....taken as	−6.0	7.4	8.6	7.5	8.6	0.1	0
0.00015.....	−3.82	7.1	8.5	7.2	8.5	0.1	0
0.01.....	−2.0	6.7	8.3	7.2	8.5	0.5	0.2
0.6.....	−0.22	5.3	7.0	6.5	7.8	1.2	0.8
6.3.....	0.8	4.1	4.3	5.7	5.9	1.6	1.6
126.0.....	2.1	2.6	2.9	3.3	3.3	0.7	0.4
355.....	2.55	2.3	2.4	2.9	2.9	0.6	0.5
2,000.....	3.3	2.0	1.9	2.0	2.0	0	0.1

TABLE II

PUPILLARY DIAMETERS AT FIXED BRIGHTNESSES

Brightness in Millilamberts	Log *B*	J.B.	C.B.	K.H.	F.J.	R.M.	R.W.	Average of 6	P. R.	Total Average
0.....taken as	−6	7.4	8.7	7.0	7.8	8.3	8.7	8.0	8.6	8.1
0.00015.....	−3.8	7.1	8.4	6.8	7.6	8.1	7.9	7.6	8.5	7.8
0.01.....	−2	6.7	8.0	6.7	7.0	7.1	6.3	7.0	8.3	7.2
1.0.....	0	5.0	5.9	4.8	5.2	4.6	4.5	5.0	6.9	5.3
10.....	1.0	3.9	4.8	3.6	4.6	3.5	3.5	4.0	4.4	4.0
55.....	1.7	3.0	3.5	3.1	3.1	3.0	2.9	3.1	3.3	3.1
100.....	2	2.7	2.9	2.7	2.9	2.8	2.9	2.8	2.9	2.8
2,000.....	3.3	2.0	—	—	—	—	—	2.0	1.9	1.9

TABLE III

RATE OF CLOSING OF THE PUPIL

Number of Picture	Time in Seconds	J.B.	C.B.	K.H.	F.J.	R.M.	R.W.	Average of 6	C.F.	C.M.	Total Average
1	0	7.4	8.7	7.0	7.8	8.3	8.7	8.0	8.0	8.6	8.1
2	.1	7.2	8.6	6.9	7.7	8.2	8.5	7.8	7.9	8.5	7.9
3	.2	6.9	8.5	6.6	7.5	7.9	8.3	7.6	7.8	8.4	7.7
4	.3	6.7	8.0	6.4	7.2	7.5	7.4	7.2	7.5	8.2	7.4
5	.4	6.3	7.5	6.1	6.9	7.2	7.1	6.8	7.2	7.9	7.0
6	.5	6.0	7.0	5.8	6.0	6.9	6.8	6.4	7.0	7.6	6.6
11	1.0	4.7	5.7	4.9	5.4	5.4	5.8	5.3	5.9	6.3	5.5
16	1.5	3.9	4.8	4.0	4.6	4.6	4.7	4.4	5.0	5.3	4.6
21	2.0	3.3	4.3	3.6	4.1	4.0	4.0	3.9	4.4	4.6	4.0
26	2.5	3.0	4.0	3.2	3.7	3.7	3.7	3.5	4.0	4.2	3.7
31	3.0	2.9	3.8	3.1	3.5	3.3	3.5	3.3	3.8	4.1	3.5
36	3.5	2.8	3.6	3.0	3.4	3.3	3.2	3.2	3.6	4.0	3.4
41	4.0	2.8	3.7	3.1	3.3	3.1	3.2	3.2	3.5	4.0	3.3
46	4.5	2.8	3.7	3.0	3.2	3.1	3.1	3.1	3.6	3.9	3.3
51	5.0	2.8	—	—	—	—	3.1	—	—	3.9	3.3
	1 min.	2.8	3.4	3.1	3.1	3.1	3.1	3.1	3.4	3.8	3.2

TABLE IV

RATE OF OPENING OF THE PUPIL

Time in Darkness	J.B.	C.B.	K.H.	F.J.	R.M.	R.W.	Average of 6	R.K.	Total Average
0	2.7	3.1	2.7	2.9	2.8	3.0	2.9	2.7	2.8
.5 sec.	3.0	3.5	2.9	3.1	3.0	3.2	3.1	3.0	3.1
1.0 "	3.2	4.0	3.2	3.6	3.6	3.7	3.5	3.5	3.5
1.5 "	3.9	4.4	3.4	4.2	3.9	3.8	3.9	3.9	3.9
3.0 "	4.7	5.3	4.3	4.7	5.0	4.4	4.7	4.3	4.7
5.0 "	5.3	6.6	4.9	5.4	5.8	5.7	5.6	4.9	5.5
9. "	5.7	7.6	5.6	6.0	6.6	6.7	6.4	5.4	6.2
15. "	5.7	8.0	5.5	6.6	6.9	6.9	6.6	6.1	6.5
29. "	5.8	8.4	6.1	7.0	7.0	7.0	6.9	6.2	6.8
1 min.	6.2	8.6	6.3	7.3	7.2	8.3	7.3	6.3	7.2
3 "	6.6	8.7	6.5	7.5	7.8	8.5	7.6	6.8	7.5
5 "	6.6	8.6	6.6	7.3	8.0	8.7	7.6	7.2	7.6
10 "	—	8.9	—	—	—	—	—	—	—

statements. This study has opened a large problem and much information awaits the treatment of other brightness combinations and the treatment of colored light sources.

The writer wishes to acknowledge the services of the members of the laboratory who so patiently acted as subjects in such a trying experiment. The writer is especially indebted to Dr. Julian Blanchard for his coöperation in the entire experiment.

PSYCHOLOGICAL REVIEW PUBLICATIONS

Original contributions and discussions intended for the Psychological Review should be addressed to

Professor Howard C. Warren, Editor PSYCHOLOGICAL REVIEW,
Princeton, New Jersey.

Original contributions and discussions intended for the Journal of Experimental Psychology should be addressed to

Professor John B. Watson, Editor JOURNAL OF EXPERIMENTAL PSYCHOLOGY,
The Johns Hopkins University, Baltimore, Maryland.

Contributions intended for the Psychological Monographs should be addressed to

Professor James R. Angell, Editor PSYCHOLOGICAL MONOGRAPHS,
University of Chicago, Chicago, Ill.

Reviews of books and articles intended for the Psychological Bulletin, announcements and notes of current interest, and *books offered for review* should be sent to

Professor S. I. Franz, Editor PSYCHOLOGICAL BULLETIN,
St. Elizabeth's, Washington, D. C.

Titles and reprints intended for the Psychological Index should be sent to

Professor Madison Bentley, Editor PSYCHOLOGICAL INDEX,
University of Illinois, Urbana, Ill.

All business communications should be addressed to

Psychological Review Company
Princeton, New Jersey.

PHILOSOPHICAL MONOGRAPHS

VOL. I

1. **Æsthetic Experience: Its Nature and Function in Epistemology.** W. D. FURRY Pp. xvi+160. $1.60. 2. **The Philosophy of John Norris of Bemerton.** FLORA ISABEL MACKINNON. Pp. iii+103. $1.00. 3. **Freedom and Purpose. An Interpretation of the Psychology of Spinoza.** JAMES H. DUNHAM. Pp. iv+126. $1.25.

LIBRARY OF GENETIC SCIENCE AND PHILOSOPHY

Vol. 1. The Moral Life. A Study in Genetic Ethics. By ARTHUR ERNEST DAVIES, PH.D., Professor of Philosophy in Ohio State University. xiv+188 pages. 8vo. Cloth. Price, $1.50 net. Postage, 10 cents.

Vol. 2. Darwin and the Humanities. By JAMES MARK BALDWIN. viii+118 pages. 8vo. Cloth. Price, $1.50 net. Postage, 8 cents.

Published by

PSYCHOLOGICAL REVIEW COMPANY

PRINCETON, N. J.

Directory of American Psychological Periodicals

American Journal of Psychology—Worcester, Mass.; Florence Chandler.
Subscription $5. 600 pages annually. Edited by G. Stanley Hall.
Quarterly. General and experimental psychology. Founded 1887.

Pedagogical Seminary—Worcester, Mass.: Florence Chandler.
Subscription $5. 575 pages annually. Edited by G. Stanley Hall.
Quarterly. Pedagogy and educational psychology. Founded 1891.

Psychological Review—Princeton, N. J.: Psychological Review Company.
Subscription (with Psychological Bulletin) $6. 480 pages annually.
Bi-monthly. General. Founded 1894. Edited by Howard C. Warren.

Psychological Bulletin—Princeton, N. J.: Psychological Review Company.
Subscription $3.25. 480 pages annually. Psychological literature.
Monthly. Founded 1904. Edited by Shepherd I. Franz.

Psychological Monographs—Princeton, N. J.: Psychological Review Company.
Subscription $4 per vol. 500 pp. Founded 1895. Ed. by James R. Angell.
Published without fixed dates, each issue one or more researches.

Psychological Index—Princeton, N. J.: Psychological Review Company.
Subscription $1.25. 200 pp. Founded 1895. Edited by Madison Bentley.
An annual bibliography of psychological literature.

Journal of Philosophy, Psychology, and Scientific Methods—New York.
Sub-Station 84. Bi-weekly. 728 pages per volume. Founded 1904.
Subscription $3. Edited by F. J. E. Woodbridge and Wendell T. Bush.

Archives of Psychology—Sub-station 84, N. Y.: Archives of Psychology.
Subscription $5. 600 pp. ann. Founded 1906. Ed. by R. S. Woodworth.
Published without fixed dates, each number a single experimental study.

Journal of Abnormal Psychology—Boston: Richard G. Badger.
Subscription $5. 480 pages annually. Edited by Morton Prince.
Bi-monthly. Founded 1906. Entire field of abnormal psychology.

Psychological Clinic—Philadelphia: Psychological Clinic Press.
Subscription $1.50. 280 pages annually. Edited by Lightner Witmer.
Monthly (9 numbers). Orthogenics, psychology, hygiene. Founded 1907.

Training School Bulletin—Vineland, N. J.: The Training School.
Subscription $1. 160 pp. ann. Ed. by E. R. Johnstone. Founded 1904.
Monthly (10 numbers). Psychology and training of defectives.

Journal of Religious Psychology—Worcester, Mass.: Louis N. Wilson.
Subscription $3. 480 pages per vol. Founded 1904. Ed. by G. Stanley Hall
Published without fixed dates. 4 numbers constitute a volume.

Journal of Race Development—Worcester, Mass.: Louis N. Wilson.
Subscription $2. 460 pages annually. Founded 1910.
Quarterly. Edited by George H. Blakeslee and G. Stanley Hall.

Journal of Educational Psychology—Baltimore: Warwick & York.
Subscription $3. 600 pages annually. Founded 1910.
Monthly (10 numbers). Managing Editor, J. Carleton Bell.
(Educational Psychology Monographs. Edited by Guy M. Whipple.
Published separately at varying prices. Same publishers.)

Journal of Animal Behavior—Cambridge, Mass.; Emerson Hall.
Subscription $5. 450 pp. annually. Founded 1911.
Bi-monthly. Robert M. Yerkes, Managing Editor.

The Behavior Monographs—Cambridge, Mass.: Emerson Hall.
Subscription $5. 450 pages per volume. Edited by John B. Watson.
Published without fixed dates, each number a single research.

Psychoanalytic Review—Washington, D. C.: 3617 10th St., N. W.
Subscription $5. 500 pages annually. Psychoanalysis.
Quarterly. Founded 1913. Ed. by W. A. White and S. E. Jelliffe.

Journal of Experimental Psychology—Princeton, N. J.
Psychological Review Company. 480 pages annually. Experimental.
Subscription $3.25. Founded 1916. Bi-monthly. Ed. by John B. Watson

Journal of Applied Psychology—Worcester, Mass.: Florence Chandler.
Subscription $4. 400 pages annually. Quarterly. Founded 1917.
Edited by G. Stanley Hall, John Wallace Baird and L. R. Geissler.

Journal of Experimental Psychology—Princeton, N. J.
Psychological Review Company. 480 pages annually. Experimental.
Founded 1915. Subscription $3. Bi-monthly. Edited by John B. Watson.